DEPARTMENT OF THE ARMY

CORPS OF ENGINEERS

MISSISSIPPI RIVER COMMISSION

IRRIGATION TUNNEL FOR ST. MARY DAM
ST. MARY-MILK RIVER PROJECT, ALBERTA, CANADA

MODEL INVESTIGATION

TECHNICAL MEMORANDUM NO. 2-262

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SYNOPSIS

Model investigations of the irrigation tunnel for St. Mary Dam, St. Mary-Milk River Project, Alberta, Canada, were conducted to examine the over-all hydraulic performance of a tunnel designed to pass a maximum discharge of 3,200 cfs under heads ranging from 25 to 81 ft. The structures included four short, high-pressure intake conduits, flow through which was controlled by four gates the outside pair being 4 ft wide by 5 ft high and the inside pair 5 ft wide by 5 ft high. These conduits discharged into a horseshoe-shaped nonpressure tunnel 17 ft high and 2,500 ft long. A flared outlet portal on the downstream end of the tunnel was designed to give a maximum recovery of velocity head.

Model tests (performed on two models built to scales of 1:25 and 1:15) verified the predicted over-all performance of the structure in that the capacity was found to be approximately that computed, a hydraulic jump formed in the tunnel for all operating conditions, and flow lines in the tunnel were approximately as anticipated. However, tests demonstrated: (a) the need for increasing the length of the intake curves to the high-pressure conduits to prevent cavitation thereon; (b) the desirability of eliminating air vents proposed in the intake conduits except those immediately downstream from the gates; and (c) modification of the outlet portal to obtain better flow distribution into the exit channel.

IRRIGATION TUNNEL FOR ST. MARY DAM

ST. MARY-MILK RIVER PROJECT, ALBERTA, CANADA

Model Investigation

PART I: INTRODUCTION*

1. The St. Mary Dam Reservoir project, at present under construction near Spring Coulee, Alberta, Canada (fig. 1), is one unit of the St. Mary-Milk River project whereby a reservoir of some 300,000 acre-ft of water to be impounded at crest stage will be available for irrigation of 345,000 acres of semi-arid land and for supplementary irrigation of an additional 120,000 acres. The project will consist of an earth dam forming a lake 15 mi in length and 6 mi in width, a spillway in the right abutment, a diversion tunnel, and an irrigation tunnel (plate 1).

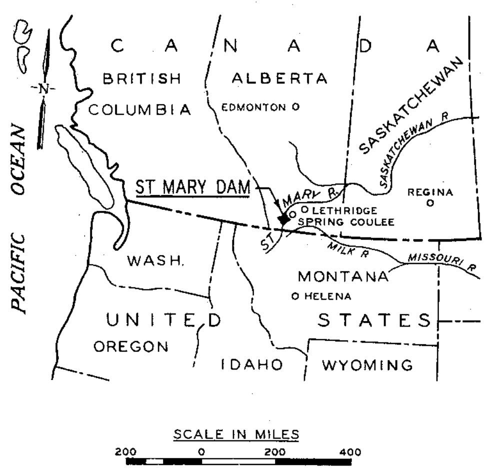

Fig. 1. Vicinity map

2. The dam will be a rolled-fill earth structure, 2700 ft in length, and will rise to a maximum height of about 185 ft above the river channel. It will have a top width of 20 ft and a bottom width

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* Information on the prototype was obtained from "Investigation and Design of the St. Mary Dam", by W. L. Foss, District Engineer, and from "The St. Mary's-Milk River Dam", by Rt. Hon. C. D. Howe, M.E.IC, Minister of Reconstruction.

from toe to toe of over one-half mile. About five million cubic yards of earth will be required for construction.

3. The spillway, to be located in the right abutment of the dam, will be of the converging chute type capable of discharging 60,000 cfs under the design head of 18 ft. Surmounting the crest will be piers 4 ft in width dividing the spillway into 12 bays, each 20 ft wide. Slots will be provided in the piers for the insertion of stop-logs, if it is desired to provide additional storage above spillway crest (elevation 3602*).

4. The diversion tunnel, to be used primarily during construction, will be concrete lined and will have a maximum design capacity of 9,000 cfs. The tunnel will be 20 ft in diameter and 2,200 ft long.

5. The irrigation tunnel, the subject of this model study, will be a 2,500-ft nonpressure tunnel capable of discharging 3,200 cfs under heads varying from 25 to 81 ft. Flow will enter the tunnel at the upstream end through four high-pressure, gate-controlled conduits -- the outside pair to be 4 ft wide by 5 ft high and the inside pair to be 5 ft high by 5 ft wide (plate 2). The tunnel will be of the horseshoe type with a maximum height of 17 ft. At its downstream end a flared outlet portal will permit an easy transition of flow from the tunnel into a trapezoidal-shaped exit channel. The exit channel will have a bottom width of 47 ft and will convey tunnel flow to a small storage pond from which it will enter the main irrigation canal.

6. To verify the design of the irrigation tunnel and its

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* All elevations are in feet above mean sea level.

appurtenant elements and to provide means for correcting any unfavorable conditions found to exist, model tests were considered desirable. Special consideration was to be given to: (a) calibration of the intake structure for various gate combinations; (b) study of pressure conditions in the high-pressure conduits; (c) location of the hydraulic jump in the tunnel under various operating conditions; and (d) examination of the performance of the outlet portal in effecting an easy transition of flow to the exit channel. Authority to undertake the model studies for the Department of Agriculture of Canada was granted by the Chief of Engineers in the second indorsement dated 20 September 1946 to a letter dated 29 August 1946 from the Waterways Experiment Station.

7. During the course of the model study, representatives of the Department of Agriculture, Canada, visited the Waterways Experiment Station to discuss test results and to correlate these results with design work concurrently being carried on by their office. The visiting party included: Mr. George Spence, Director of Rehabilitation; Mr. G. L. MacKenzie, Chief Engineer; Mr. W. L. Foss, Project Engineer; Mr. G. W. Parkinson, Mechanical Engineer; Mr. R. Peterson, Soils Mechanics Engineer; and Major General Harley B. Ferguson, U. S. Army, retired, Consulting Engineer. Engineers of the Waterways Experiment Station actively connected with the model study were: Messrs. E. P. Fortson, Jr., F. R. Brown, T. E. Murphy, R. G. Cox, and N. V. Cowan.

PART II: THE MODELS

8. The model of the irrigation tunnel for St. Mary Dam (fig. 2) was constructed to an undistorted scale of 1:25 and reproduced 200 ft of the approach channel, the entire tunnel, including the intake structure and transition, the tunnel proper, the flared outlet portal, and 300 ft of exit channel. The reservoir area was represented by a reinforced concrete headbay properly baffled and of sufficient size to insure representative approach conditions to the intake structure. The portion of the approach channel contained in the headbay was molded in cement mortar to sheet-metal templets. The entire tunnel, including intake structure and transition, tunnel proper, and outlet portal, was molded of transparent plastic which permitted direct observation of flow. The exit

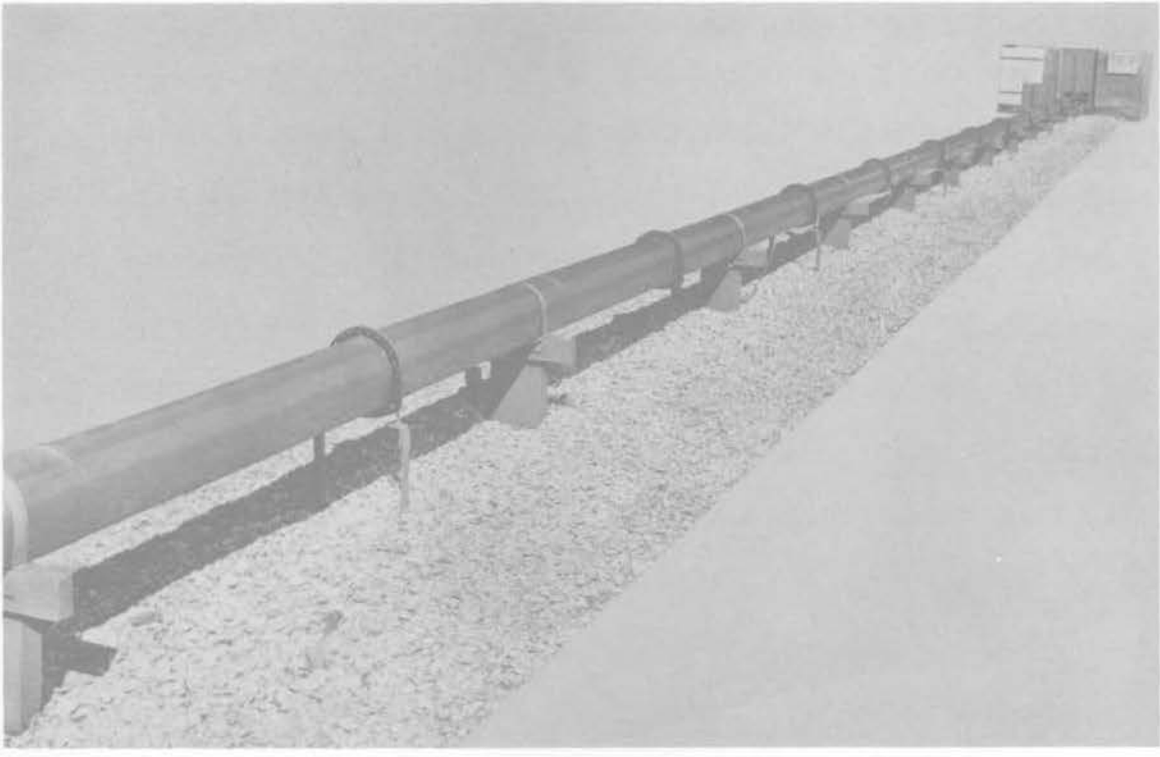


Fig. 2. General view of model tunnel looking toward headbay

channel was molded in cement mortar in a manner similar to that of the approach channel.

9. Water used for operation of the model was supplied by a circulating system containing numerous centrifugal and axial-flow pumps permitting flexibility in operation. Measurement of flow was accomplished by means of two venturi meters of different size. Flow was introduced into the model through a series of baffle walls and a stilling pool which provided entrance conditions representative of the prototype reservoir pool. After passing through the model, the water was returned to the circulating system through a return conduit. The tailwater elevation was controlled by a hinged gate at the lower end of the exit channel. A fixed reference plane was established over the exit channel by setting longitudinal steel rails on both sides. Across these rails was placed a movable cross rail mounted with point gage and pitot tube by which means water-surface elevations and velocity measurements could be obtained anywhere in the exit channel. Two piezometer gages, one located in the headbay and the other in the exit channel, were used in conjunction with hook gages mounted outside the model to obtain accurate measurement of pool and tailwater elevations. Numerous piezometer openings were located at critical points in the intake structure and tunnel sections. These piezometer openings, connected to glass manometers by flexible tubing, provided means of obtaining pressure gradients throughout the model.

10. During the course of the model study, supplementary tests for more detailed study of flow through one of the high-pressure conduits were indicated. Accordingly, a model was constructed of one of the

5-ft-wide by 5-ft-high pressure conduits and intake through which flow is introduced into the tunnel. This model was constructed entirely of transparent plastic to a scale of 1:15. The whole model was then placed in a steel vacuum tank for investigation at reduced pressure (see fig. 4, page 11). The tank was 5 ft wide, 5 ft high, and 15 ft long. It was divided into a headbay and tailbay by a temporary wooden bulkhead. Windows in the top and one side of the tank permitted direct observation of flow through the model. A vacuum pump connected to the tank was capable of reducing the air pressure in the system to as low as 0.25 in. of mercury (absolute pressure). Water was circulated through the tank by a centrifugal pump located in a pipe line between the tailbay and headbay ends of the tank. Means were provided for measuring the amount of water being circulated, the temperature of the water, and the air pressure within the system.

11. The accurate reproduction of hydraulic phenomena in a small-scale model requires geometric and dynamic similarity of the model to its prototype. Geometric similitude is readily attained by carefully constructing the model to the scale ratio selected. True dynamic similarity makes more rigorous demands. In practice, however, it is not necessary to reach perfection, as a model study is feasible provided (a) one of the dynamic forces involved predominates, (b) similitude with respect to the predominating force is attained, and (c) the limitations imposed by the lesser forces are duly considered.

12. For the case at hand, geometric similitude was assured between model and prototype by selecting an undistorted scale ratio and carefully constructing all model elements thereto. Since gravity was

the predominating force affecting fluid motion, dynamic similarity was attained by varying all hydraulic quantities in accordance with the Froudian relationships. In meeting the requirements for dynamic similarity of model and prototype, the model representation of prototype surfaces must be smoother as the scale ratio decreases. For the scale ratios of 1:25 and 1:15 adopted for the two models used in the study and an assumed prototype roughness value of 0.013, the model roughness theoretically should be about 0.0077 and 0.0083, respectively. The actual roughness value for the plastic material with which the models were constructed had been found during previous tests to be close to that desired.

13. Relationships for transference of model data to prototype, or vice versa, are expressed by the following tabulation, where the subscript "r" represents model-to-prototype ratio:

	Relationship	
Dimension	Comprehensive Model	Intake Model
Length	$L_r = 1:25$	1:15
Area	$A_r = L_r^2 = 1:625$	1:225
Velocity	$V_r = L_r^{1/2} = 1:5$	1:3.873
Discharge	$Q_r = L_r^{5/2} = 1:3125$	1:872
Roughness	$N_r = L_r^{1/6} = 1:1.710$	1:1.570

PART III: DESCRIPTION OF TESTS

Intake Structure

Original design

14. The intake structure consisted of four high-pressure conduits through which flow was introduced into the tunnel. See plate 3 and fig. 3. Flow through the two outside conduits was controlled by slide gates 4 ft wide by 5 ft high while flow through the two inside conduits was controlled by slide gates 5 ft by 5 ft. Twin gates were contemplated for each conduit, the downstream one to be a service gate and the upstream

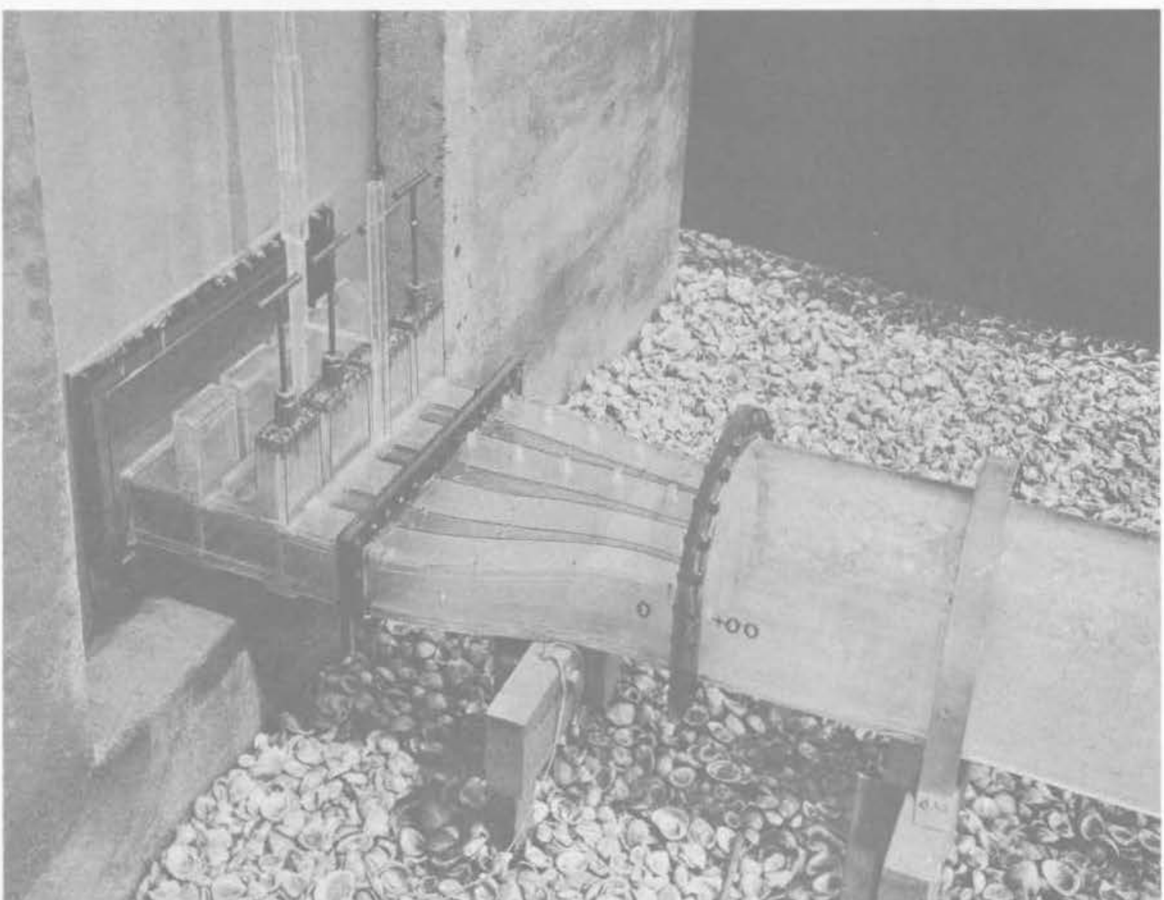


Fig. 3. Intake and transition

one an emergency gate. Each gate was followed by a 2-in. stepdown in the roof and floor of the conduit. The intake curves of original design for the roof and sides of all conduits were shaped to the equation

$$\frac{X^2}{(0.5013D)^2} + \frac{Y^2}{(0.15041D)^2} = 1,$$

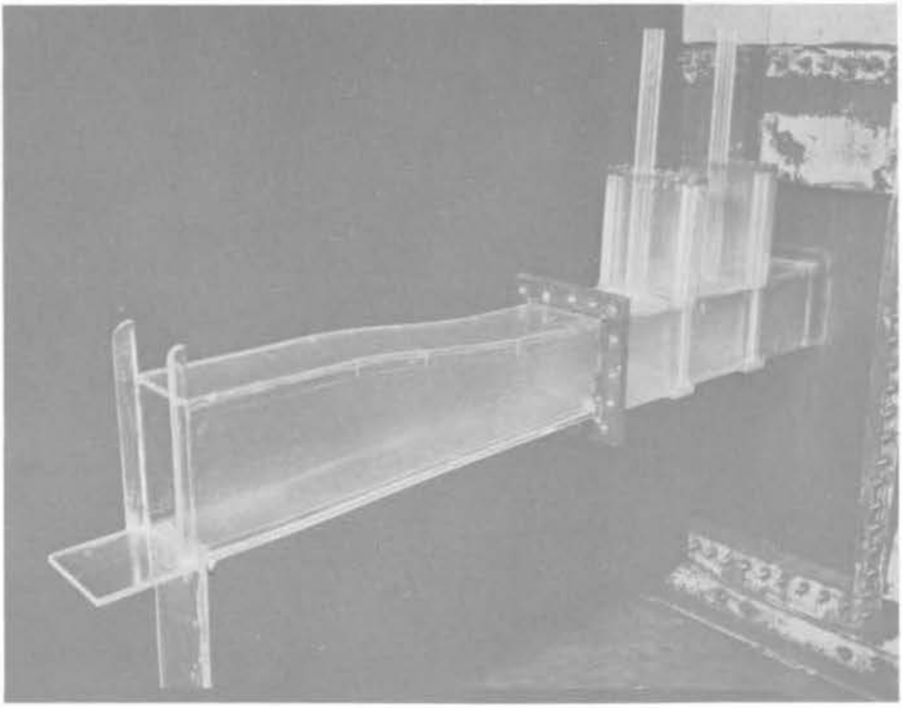
where D was equal to the distance across the conduit in the direction concerned. The floor of the conduits at the intake was level with the bottom of the approach channel. Air vents were provided behind each gate and on the inside of bends as shown on plate 3.

15. The intake conduits were calibrated in the 1:25-scale general model and the resulting discharge curves are presented as plate 4. Actual calibration data were measured only for conditions with one outside, one inside, and all four conduits in operation. Discharges for other various combinations of conduits were compiled mathematically from data obtained by single conduit operation and spot checked in the model. The model showed that the capacity of a conduit was not affected by operation of other conduits. Initial information on tailwater elevation was that a constant elevation of 3545 would be maintained at the tunnel outlet. Therefore, initial calibration tests were conducted with the tailwater at this elevation. To study the effect of tailwater on discharge capacity, the conduits also were calibrated with the tailwater at the tunnel outlet lowered as much as possible. As indicated on plate 4 some increase in capacity was secured at low pool levels. Later a prototype tailwater rating curve (plate 5) was received and calibration of the conduits was repeated with the tailwater set at the proper elevations. Data obtained revealed that the expected tailwater would have no

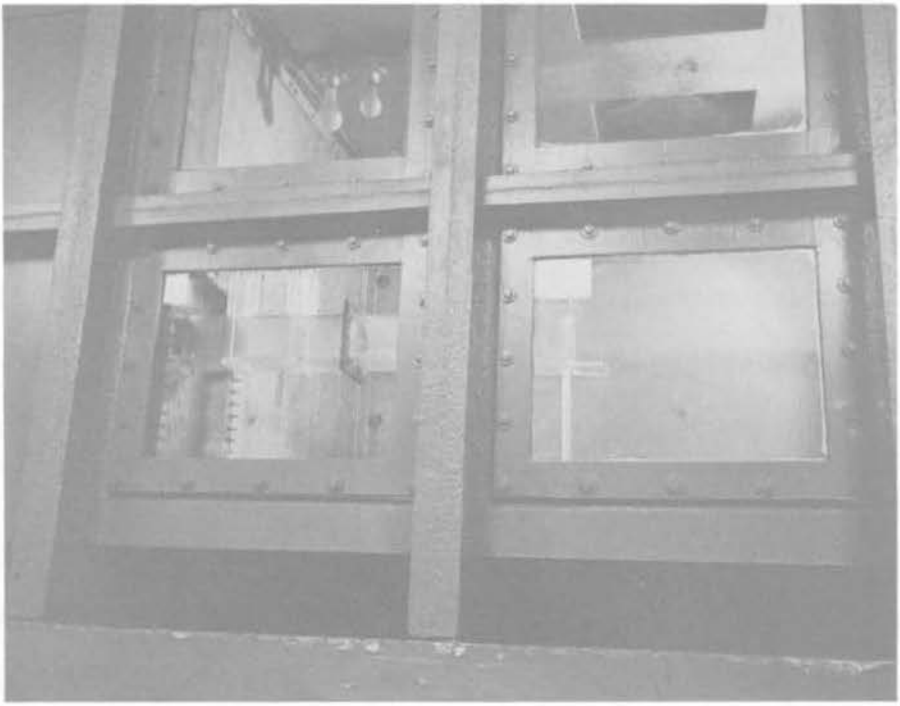
effect on the capacity of the conduits and that the discharge curves obtained on the model with tailwater set as low as possible would apply to the prototype.

16. Pressures measured in the intake structure of the 1:25-scale model for various operating conditions are listed in tables 1-5. Piezometer locations are shown on plate 6. Pressure data were obtained with the air vents behind the gates open but with the air vents on the inside of the bends closed. Minimum pressures of about -16 ft of water were measured on the intake curves while pressures of about -14 ft of water were measured on the inside of the bends in the conduits. Pressures were difficult to record since, even with the gates fully open, air was drawn down the vents behind the service gates and entered the path of flow. With the air vents on the inside of the bends opened, air also was drawn into the path of flow, resulting in considerable turbulence.

17. Since pressures dangerously near the cavitation range were measured in the intake conduits, a model of one of the 5-ft by 5-ft conduits was fabricated to a scale of 1:15 and tested in an existing vacuum tank (fig. 4 and paragraph 10). If a model is to simulate cavitation conditions in the prototype, it is necessary to inclose the model in a tank or closed system from which the air is partially exhausted so that the atmospheric pressure on all free surfaces (headwater and tailwater areas) is reproduced in exact proportion to the model scale. Theoretically, the temperature of the model water should have been chilled also to reduce the vapor pressure in accordance with the model scale. However, this latter step was not necessary, since in the model it was possible to record the temperature of the model fluid from which the vapor pressure



View of conduit from inside tank



View of conduit through tank observation windows

Fig. 4. General views of 5-ft by 5-ft high-pressure conduit installed in vacuum tank

could be determined. The air pressure necessary in the tank to simulate prototype conditions was then computed as follows:

$$\frac{P_a - P_{v_1}}{L} = P_t - P_{v_2}$$

where

P_a = atmospheric pressure at dam site in inches of mercury

P_{v_1} = vapor pressure of prototype water in inches of mercury

L = linear scale of model

P_t = tank pressure in inches of mercury

P_{v_2} = vapor pressure of model water in inches of mercury.

18. During the present series of tests, the head and tailwater were set first to produce the desired flow conditions through the one 5- by 5-ft high-pressure conduit reproduced. Then the tank pressure was raised or lowered, depending on whether or not cavitation flashes were already present, and the point observed at which cavitation became incipient for any set of flow conditions. When the point of incipient cavitation was determined, the water temperature and barometric and tank pressures were recorded. From the model data procured the equivalent atmospheric pressure at which incipient cavitation would occur in the prototype was then computed by the formula presented above.

19. Plate 7 presents a plot of the equivalent atmospheric pressure at which incipient cavitation occurred for various conditions of head and four shapes of intake. These data are based on an assumed average water temperature in the prototype of 50 degrees Fahrenheit. At the dam site atmospheric pressure in the prototype would be about 26.3 in. of mercury.

20. The curve labeled test 1 defines the points of incipient cavitation for various heads on the intake of original design. This curve shows that with the pool at elevation 3620 and an assumed prototype water temperature of 50° F, cavitation flashes began to appear when the pressure in the tank was reduced to an equivalent prototype atmospheric pressure of about 26 in. of mercury. As the pool level was lowered the velocity of flow decreased and it was necessary to reduce the hypothetical atmospheric pressure simulated in the tank to cause the flashes to appear. Thus, for normal conditions at the St. Mary Dam site, with a water temperature of 50° F, there appears to be a definite possibility for cavitation at high levels. As the temperature of the water in the prototype rises above 50° F cavitation also will occur at lower pool levels. In analyzing the data presented on plate 7, it is desired to emphasize that, although equivalent atmospheric pressures as low as 20 in. of mercury and lower are impossible to obtain in the prototype, the tank pressure had to be lowered to reproduce these hypothetical equivalent atmospheric pressures to induce cavitation flashes.

21. With all air vents closed and the service gate fully open, it was observed as the tank pressure was reduced that cavitation flashes appeared first on the roof of the conduit at the downstream edge of the gate passage, then at the corners of the intake, and last along the inside curvature of the bends. However, the tank pressure had to be lowered so much to produce cavitation flashes along the inside curvature of the bends, no cavitation should occur under prototype conditions. These tests indicate the desirability of air vents downstream from the service gates, and the elimination of the vents along the inside curvature of the bends.

Revised design.

22. The intake curves for the roof and sides of the type 2 intake were shaped to the equation:

$$\frac{X^2}{(0.75D)^2} + \frac{Y^2}{(0.25D)^2} = 1.$$

The 2-in. stepdown in the roof and floor of the conduit following each gate was eliminated and the downstream edges of the gate slots were tapered (plate 8). Although the intake curve of type 2 provided an easier transition of flow into the conduit, the elimination of the stepdown at the gates resulted in pressure conditions about the same as observed with the original curved intake (plate 7). However, the type 2 intake increased the capacity of the conduit about 20 per cent over the capacity of the original design. The resulting increased velocity would account in part for the pressure reduction.

23. The type 3 intake had the top curve shaped to the equation:

$$\frac{X^2}{(0.5013D)^2} + \frac{Y^2}{(0.30082D)^2} = 1,$$

while the side curves of original design were retained. Tests in the vacuum tank revealed that cavitation tendencies on the top corners of the intake were increased considerably over those observed previously with the types 1 and 2 intakes (plate 7). For a pool elevation as low as 3580, cavitation in the prototype appears inevitable if the type 3 intake were to be installed. Capacity of flow through the conduit with the type 3 intake was about the same as with type 2.

24. Although modification of the roof of the conduits and the gate slots had increased the capacity of the conduit, Canadian engineers stated that it was desired to retain the original gate unless the design

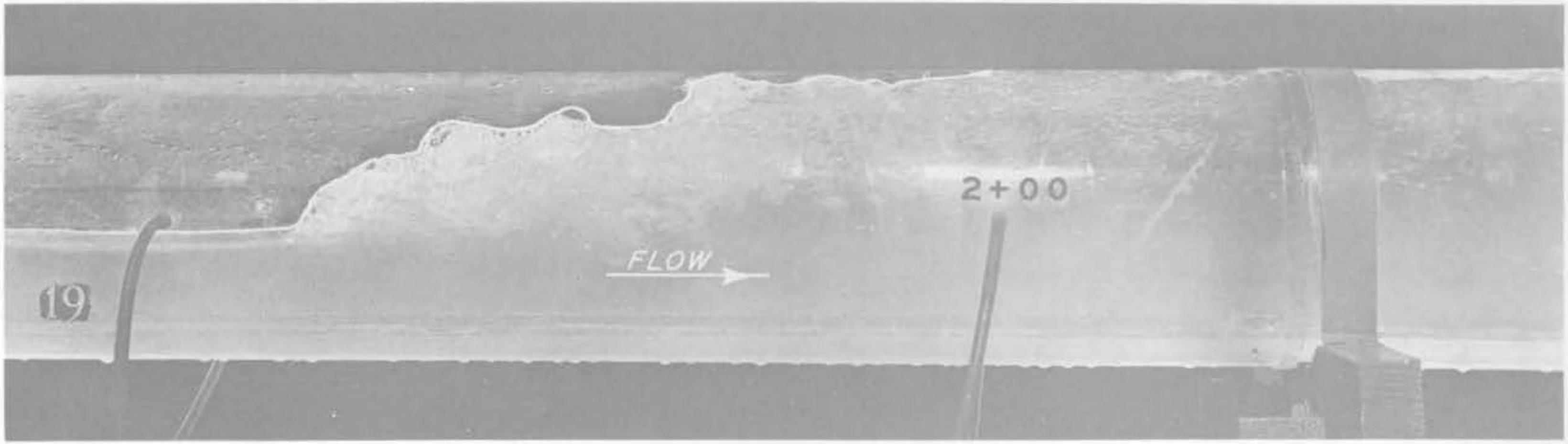
was considered unsafe. Since the air vents immediately downstream from the gates prevented cavitation on the roof of the conduit at the downstream edge of the gate passage, this design was considered adequate. Consequently, the original stepdown below the gate passage and gate slots was reinstalled and tested in conjunction with the intake curves used in the type 2 intake. This arrangement was designated the type 4 intake.

25. The 2-in. stepdown in the roof of the conduit provided enough back pressure to eliminate cavitation flashes on the intake curves of the type 4 design until the tank pressure was at an equivalent atmospheric pressure of 10 in. of mercury (curve designated test 4 on plate 7). An atmospheric pressure as low as 10 in. of mercury could never exist at the prototype site which insures the safety of the structure from cavitation with the type 4 intake installed. Capacity was about equal to that observed with the intake of original design (see insert, plate 7).

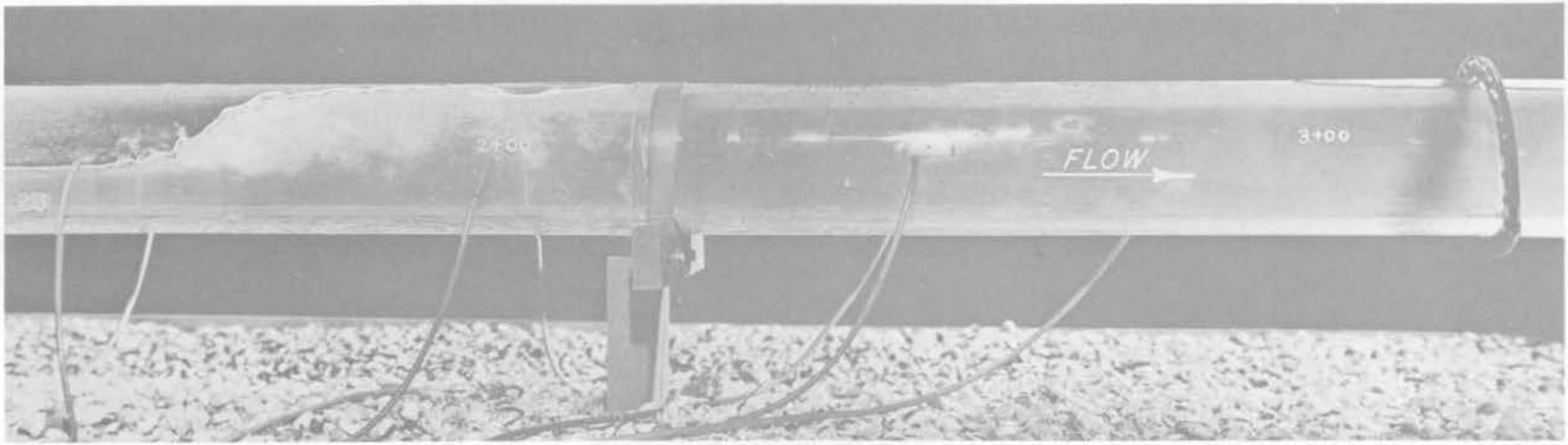
Tunnel

26. Flow passed from the high-pressure conduits through a transition (plate 9) to the tunnel proper. As explained previously, the tunnel was designed to operate as a nonpressure tunnel; i.e., it would never flow full.

27. As planned, a hydraulic jump formed in the tunnel for all operating conditions. Fig. 5, 6, and 7 present views of the hydraulic jump in the tunnel for different flow conditions, and plate 10 shows a plot of the actual water-surface profile existing. Pressures measured

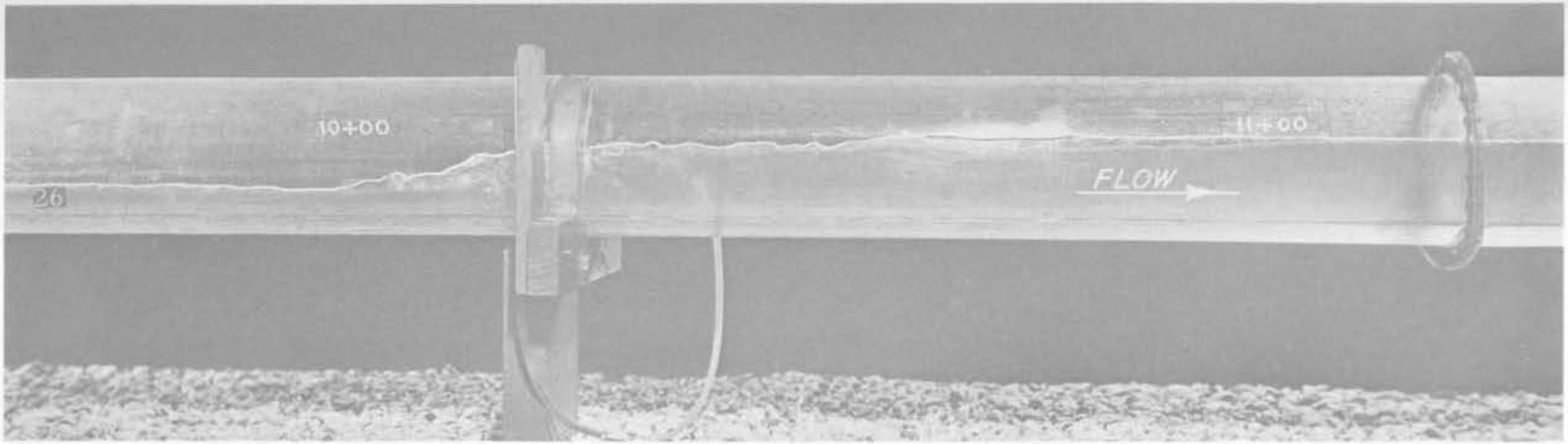


Close-up of jump

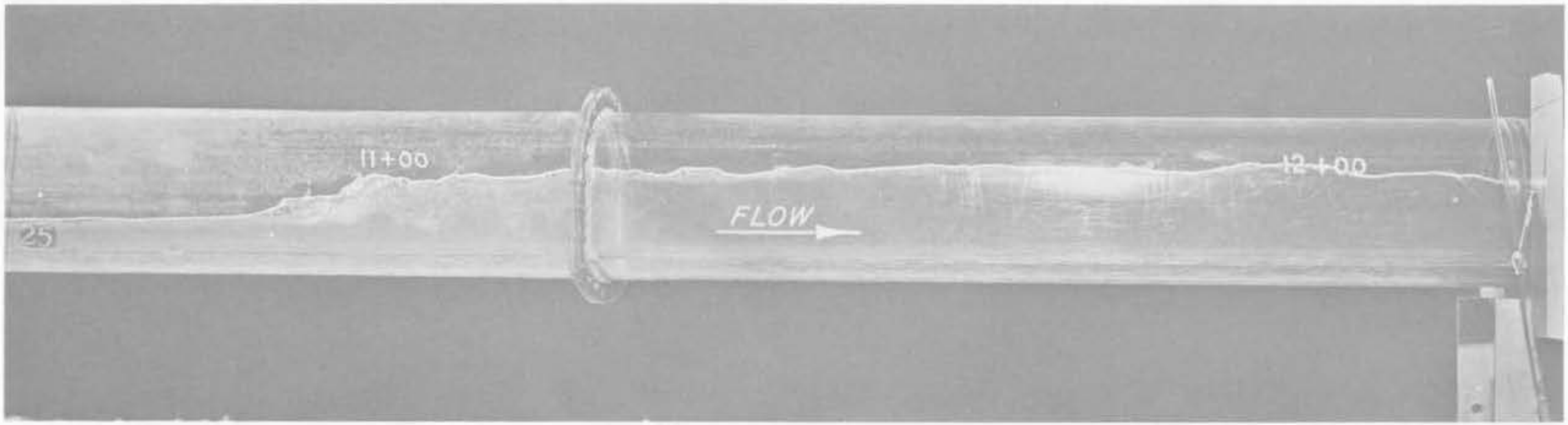


Jump and flow line

Fig. 5. Hydraulic jump and flow line in tunnel, all conduits operating; discharge, 3200 cfs; tailwater elevation, 3545.7 ft

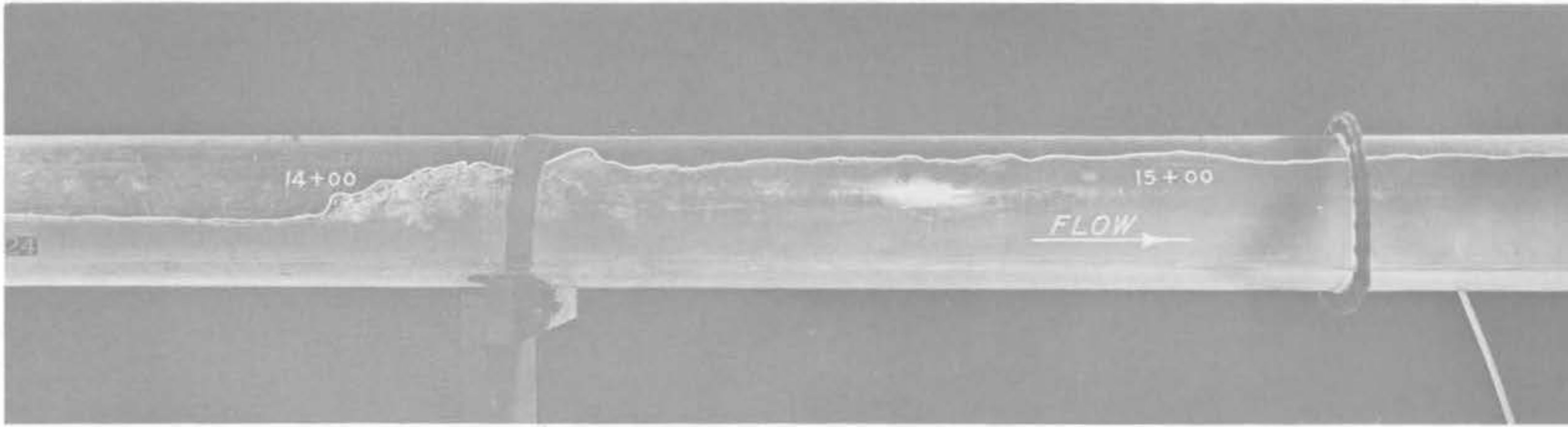


4- by 5-ft conduit operating; discharge, 1340 cfs; tailwater elevation, 3540.7 ft

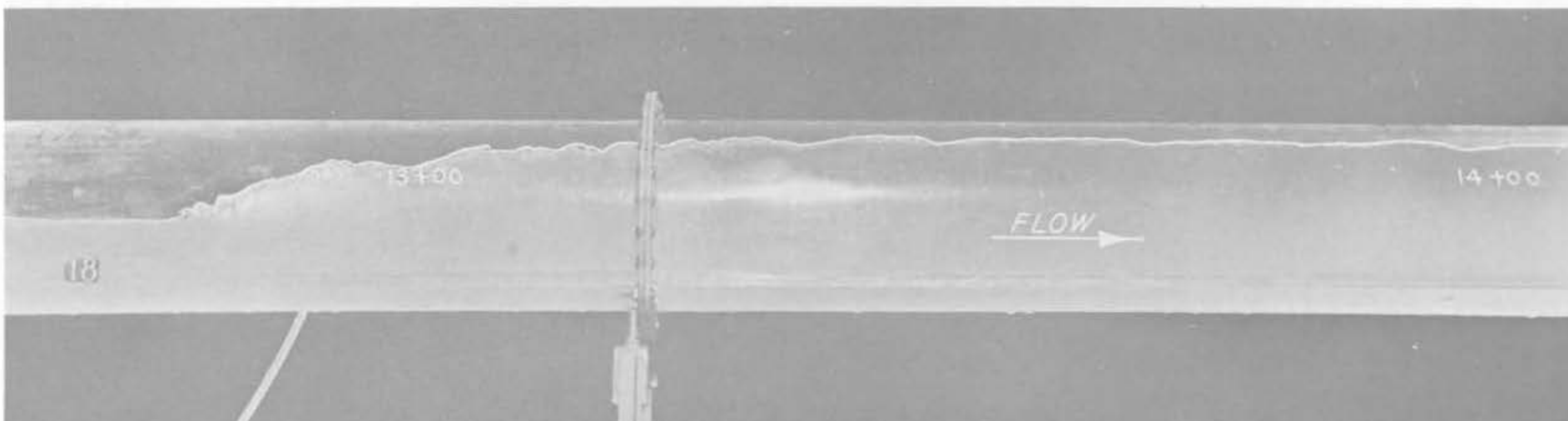


5- by 5-ft conduit operating; discharge, 1702 cfs; tailwater elevation, 3541.8 ft

Fig. 6. Hydraulic jump and flow line in tunnel
with one outside conduit in operation, and with one inside
conduit in operation



Two 4- by 5-ft conduits operating; discharge, 2680 cfs; tailwater elevation, 3544 ft



Two 5- by 5-ft conduits operating; discharge, 3200 cfs; tailwater elevation, 3545 ft

Fig. 7. Hydraulic jump and flow line in tunnel
with two outside conduits in operation, and with two inside
conduits in operation

throughout the tunnel are shown in table 6. It is to be noted that with a discharge of 3,200 cfs through all four conduits (pool elevation 3563.5) the hydraulic jump formed at about sta 1+90 (fig. 5 and plate 10). For this condition the tunnel was filled with a mixture of air and water for a distance of about 100 ft below the jump. For the remaining length of tunnel a free water surface obtained. The location of the jump appeared stable and the filling of the conduit immediately downstream did not appear to create any surge conditions. Closure of the air vent at the beginning of the tunnel transition caused the jump to move upstream to the end of the piers separating the high-pressure conduits and caused a greater length of tunnel to flow full.

28. For a discharge of 3,200 cfs through the two inside conduits (pool elevation 3612.5) a hydraulic jump formed at sta 13+00 (fig. 7) and a free water surface obtained throughout the entire length of tunnel. For this condition, closure of the air vent at the beginning of the tunnel transition had no effect.

Tunnel Outlet

Original design

29. A flared tunnel outlet was proposed in order to provide a smooth transition of flow to the exit channel and to prevent the tunnel from filling at the lower end. Details of the original design (type 1) outlet are shown on fig. 8 and plate 11. Observation of flow conditions revealed that the outlet did not function entirely as planned. Flow emerging from the type 1 outlet was forced against one side of the exit channel and an eddy formed in the opposite side (plate 13). The

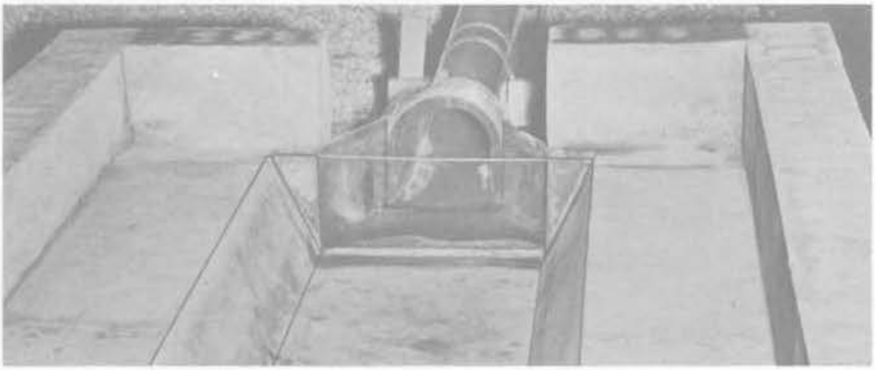


Fig. 8
Type 1 outlet
(original design)

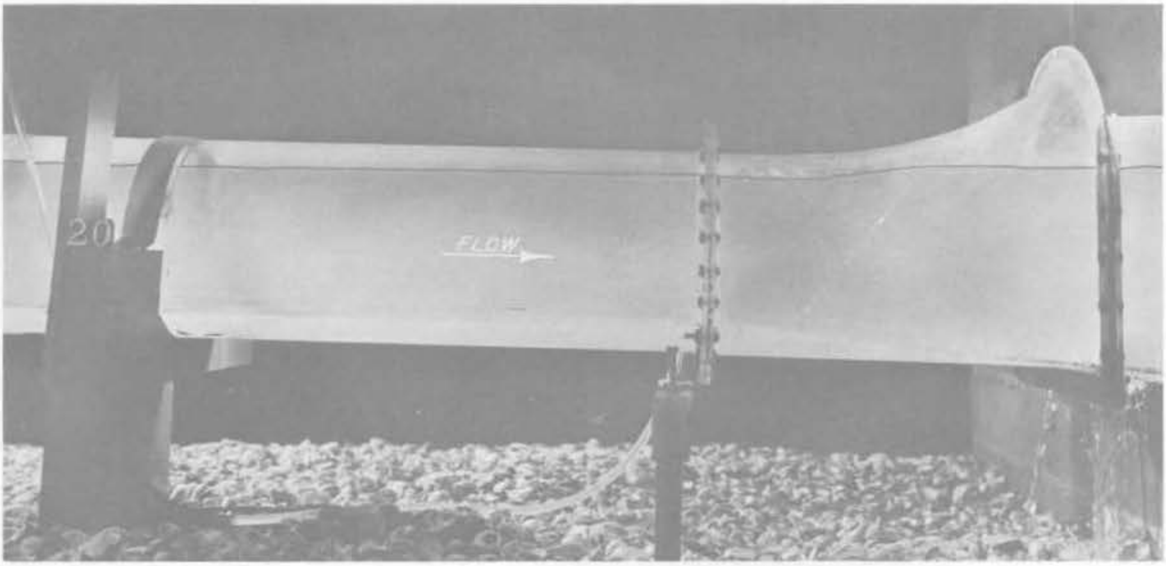


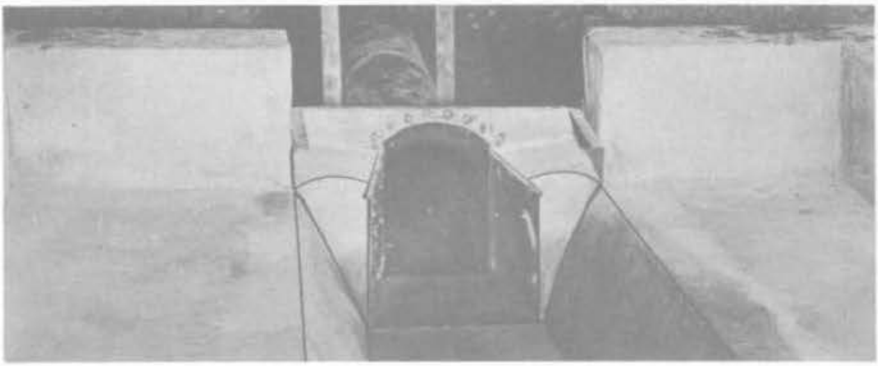
Fig. 9. Flow line in tunnel and outlet portal, original design; discharge, 3200 cfs; tailwater elevation, 3545.7 ft

water-surface profile showed a sharp rise at the outlet portal (fig. 9), although the tunnel was not filled.

Revised designs

30. Three modifications (types 2, 3, and 4) of the tunnel outlet (fig. 10 and plate 12) were investigated in an attempt to secure better distribution of flow into the exit channel. These modifications involved the elimination of the reverse curvature of the original design outlet and the use of straight side walls diverging in a downstream

Fig. 10
Type 4 outlet
(revised design)



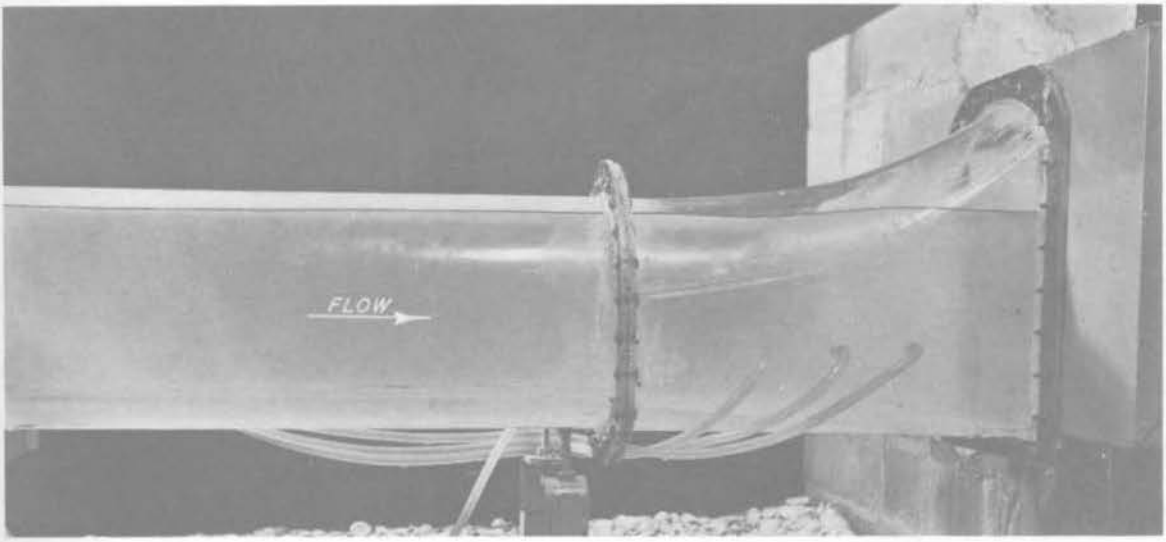


Fig. 11. Flow line in tunnel and outlet portal, revised design; discharge, 3200 cfs; tailwater elevation, 3545.7 ft

direction at a flat angle.

31. Test results are summarized by the data contained on plates 13 and 14. Types 2 and 3 designs did not produce the desired results, although use of the type 3 design did reduce the size of the eddy adjacent to the right wall. The type 4 outlet completely eliminated all eddy action and spread the flow evenly across the exit channel. The water-surface profile through the type 4 outlet did not show the sharp rise noticeable in the profile through the type 1 outlet (compare fig. 9 and 11).

PART IV: DISCUSSION

32. Although the model studies of the irrigation tunnel for St. Mary Dam verified the predicted performance of the structure, the need for modification of the design of the intake conduits and outlet transition was detected. The tests furnished means for development of the required improvements.

33. Under the maximum operating head, cavitation was found to occur in the top corners of the entrances to the conduits of original design. The danger of possible cavitation was eliminated by increasing the length of the intake curves by about 50 per cent to provide an easier transition of flow into the conduit proper. It is believed that the entrance curves of original design would have been satisfactory had they been used for circular entrances but that the tendency for flow to pull away from the corners of a rectangular entrance made a larger opening necessary to prevent cavitation in the corners.

34. The model tests also indicated the desirability of the air vents immediately downstream from the service gates and at the junction of the high-pressure conduits with the single nonpressure tunnel. The latter vent was necessary to position the hydraulic jump in the tunnel downstream. Closure of this vent caused the jump to move upstream to the end of the high-pressure conduits and resulted in a greater length of the tunnel flowing full. Air vents on the insides of the bends and on the flared roof of the high-pressure conduits introduced air into a swift flowing stream of water, intensifying turbulent conditions within the conduit. Although closure of these vents resulted in pressures below

atmospheric, it is recommended that they be closed to provide smoother flow conditions. Tests at reduced pressures demonstrated that the elimination of the vents would not result in pressures in the cavitation range at the bends or at the flared roof.

35. Observation of flow conditions in the nonpressure tunnel for a discharge of 3200 cfs revealed that the location of the hydraulic jump in the tunnel varied between sta 1+90 and sta 13+00. The jump, once formed, remained in one location. The filling of the tunnel for a short distance immediately below the jump did not create a surge condition in the tunnel and it is felt that operation of the prototype tunnel under these conditions will produce no harmful effects. Since the location of the jump was very sensitive to changes in the tailwater, it also probably would be very sensitive to changes in the surface roughness of the interior of the tunnel. Although the model roughness was approximately equivalent to the expected prototype roughness, minor differences would produce changes in the location of the jump. However, it is not believed that these differences in roughness values could be great enough to cause the jump to move back against the ends of the piers or to be swept out of the tunnel.

36. Flow from the tunnel outlet did not follow the flare of the initial design. This condition resulted in the formation of an eddy adjacent to one side of the exit channel and the confinement of high-velocity flow adjacent to the opposite side, and a rise in water-surface elevation within the outlet portal. It was possible to cause a more even distribution of flow into the exit channel and a reduction in water-surface elevations within the outlet portal by reducing the

amount of flare. The decrease in flare also reduced the amount of excavation required.

TABLES

TABLE 1

PRESSURES IN CONDUITS

Piez. No.	Piez. Zero	One Outside Conduit in Operation Dischg, 1340 cfs Pool Elev, 3620	Dischg, 1080 cfs Pool Elev, 3589	Dischg, 710 cfs Pool Elev, 3563.5
1	3539.5	10.5	7.5	5.5
2	3538.5	8.5	7.5	6.2
3	3539.5	-0.5	0.0	2.5
4	3538.5	5.0	3.9	4.5
5	3539.5	7.5	4.5	4.5
6	3539.0	11.0	7.0	6.0
7	3538.8	4.2	3.7	4.2
8	3538.7	0.3	1.0	3.3
9	3541.8	-1.8	0.2	1.7
10	3541.6	-13.6	-9.1	-2.1
11	3541.6	-12.1	-7.6	-2.1
12	3541.5	-12.5	-9.8	-2.5
13	3541.5	-2.5	-2.5	-0.5
14	3541.5	0.5	-0.5	0.2
15	3541.5	8.5	5.5	3.5
32	3541.2	-4.2	-0.7	1.3
33	3541.3	-3.3	-2.6	0.7
34	3541.7	-1.2	-1.7	0.8
35	3542.2	0.3	-0.9	0.7
36	3542.5	-0.5	-0.5	0.4
37	3542.4	-3.4	-2.4	-0.9
44	3536.1	5.9	4.9	6.4
45	3535.9	1.1	2.1	4.8
46	3535.7	-0.7	0.3	5.0
50	3538.7	-8.2	-3.7	1.3
51	3538.7	*	*	*
52	3538.7	-2.2	-1.2	2.3
53	3538.7	-1.7	-1.2	2.3
54	3538.7	-10.2	-4.7	0.8
55	3538.7	-11.2	-5.7	-0.2
56	3538.7	-5.7	-3.7	1.3
57	3538.7	-3.7	2.2	1.8

NOTE: Pressures are recorded in prototype feet of water to the nearest tenth of a foot.
Locations of piezometers are shown on plate 6.
* Denotes piezometer opening partially free of water.

TABLE 2

PRESSURES IN CONDUITS

Piez. No.	Piez. Zero	One Inside Conduit in Operation Dischg, 1702 cfs Pool Elev, 3620	Dischg, 1300 cfs Pool Elev, 3589	Dischg, 910 cfs Pool Elev, 3563.5
16	3539.5	5.0	3.5	6.5
17	3538.5			
18	3539.5	1.5	0.5	1.5
19	3538.5	2.3	1.0	2.5
20	3539.5	0.5	-0.5	0.5
21	3538.5	9.5	6.2	4.5
22	3539.0	10.5	6.0	4.0
23	3538.8	2.2	1.2	2.2
24	3538.7	-1.7	-1.7	1.3
25	3541.8	-2.8	-3.8	-1.8
26	3541.6	-8.6	-6.6	-2.6
27	3541.6	-9.3	-7.6	-3.1
28	3541.5	-8.0	-6.5	-2.5
29	3541.5	-2.0	-2.5	-1.5
30	3541.5	1.0	-0.8	-0.5
31	3541.5	6.5	3.0	1.5
38	3541.2	*	*	*
39	3541.3	*	*	*
40	3541.7	*	*	*
41	3542.2	*	*	*
42	3542.5	*	*	*
43	3542.4	*	*	*
47	3536.1	-1.1	-0.4	2.9
48	3535.9	-5.4	-3.2	2.1
49	3535.7	-3.7	-3.0	2.8
58	3538.7	*	*	*
59	3538.7	-7.7	-5.7	-0.7
60	3538.7	-12.7	-8.7	-2.2
61	3538.7	-12.7	-8.7	-2.2
62	3538.7	-10.7	-6.7	-1.7
63	3538.7	-6.7	-4.7	-0.7

NOTE: Pressures are recorded in prototype feet of water to the nearest tenth of a foot.
Locations of piezometers are shown on plate 6.
* Denotes piezometer opening partially free of water.

TABLE 3

PRESSURES IN CONDUITS

Piezometer Number Outside Conduit	Piezometer Number Inside Conduit	Piez. Zero	Two Outside Conduits in Operation Discharge, 2680 cfs Pool Elev, 3620	Two Inside Conduits in Operation Discharge, 3404 cfs Pool Elev, 3620
1	16	3539.5	8.0	-8.0
2	17	3538.5	7.5	
3	18	3539.5	-0.8	-6.5
4	19	3538.5	4.5	-3.5
5	20	3539.5	7.5	-4.5
	21	3538.5		6.0
6	22	3539.0	11.0	8.0
7	23	3538.8	4.7	2.2
8	24	3538.7	0.8	-1.7
9	25	3541.8	-1.8	-13.8
10	26	3541.6	-13.6	-12.6
11	27	3541.6	-11.6	-15.6
12	28	3541.5	-13.5	-8.0
13	29	3541.5	-2.5	-6.0
14	30	3541.5	0.5	0.0
15	31	3541.5	8.5	5.0
32	38	3541.2	*	*
33	39	3541.3	*	*
34	40	3541.7	-5.7	*
35	41	3542.2	-3.5	*
36	42	3542.5	-0.5	*
37	43	3542.4	*	*
44	47	3536.1	0.9	-2.1
45	48	3535.9	-0.9	-6.9
46	49	3535.7	-1.2	-4.7
50	58	3538.7	*	*
51	59	3538.7	*	-8.7
52		3538.7	*	
53		3538.7	*	
54	60	3538.7	-14.7	-13.7
55	61	3538.7	-11.7	-13.7
56	62	3538.7	-3.7	-11.2
57	63	3538.7	*	-6.7

NOTE: Pressures are recorded in prototype feet of water to the nearest tenth of a foot.
Locations of piezometers are shown on plate 6.
* Denotes piezometer opening partially free of water.

TABLE 4

PRESSURES IN CONDUITS

Piez. No.	Outside Conduit Piez. Zero	One Inside and One Outside Conduit in Operation	Four Conduits in Operation
		Discharge, 3035 cfs Pool Elev, 3620	Discharge, 3200 cfs Pool Elev, 3563.5
1	3539.5	-2.5	1.5
2	3538.5	-3.5	0.5
3	3539.5	-5.5	-1.0
4	3538.5	-0.5	2.0
5	3539.5	4.2	1.5
6	3539.0	11.1	4.2
7	3538.8	5.2	3.7
8	3538.7	0.3	-4.8
9	3541.8	-11.8	-2.8
10	3541.6	-15.6	-5.6
11	3541.6	-16.6	-5.3
12	3541.5	-14.5	-4.5
13	3541.5	-5.5	-2.5
14	3541.5	-1.5	-0.5
15	3541.5	-8.5	2.0
32	3541.2	-6.2	0.5
33	3541.3	-4.3	-0.7
34	3541.7	-1.7	-0.2
35	3542.2	-0.2	-0.5
36	3542.5	0.5	-0.5
37	3542.4	-3.4	-1.4
44	3536.1	*	5.2
45	3535.9	-1.1	4.1
46	3535.7	-0.7	3.5
50	3538.7	-8.2	0.1
51	3538.7	-12.7	-0.7
52	3538.7	-2.7	1.3
53	3538.7	-3.7	1.3
54	3538.7	-13.7	-1.8
55	3538.7	-12.2	-1.6
56	3538.7	-6.7	0.1
57	3538.7	-18.7	0.5

NOTE: Pressures are recorded in prototype feet of water to the nearest tenth of a foot.
Locations of piezometers are shown on plate 6.
* Denotes piezometer opening partially free of water.

TABLE 5

PRESSURES IN CONDUITS

Piez. No.	Inside Conduit Piez. Zero	One Inside and One Outside Conduit in Operation Discharge, 3035 cfs Pool Elev, 3620	Four Conduits in Operation Discharge, 3200 cfs Pool Elev, 3563.5
16	3539.5	4.5	3.5
17	3538.5	17.3	-0.7
18	3539.5	8.0	0.5
19	3538.5	6.1	1.5
20	3539.5	3.5	-0.5
21	3538.5	11.0	3.5
22	3539.0	8.1	3.5
23	3538.8	2.7	2.2
24	3538.7	-1.7	1.1
25	3541.8	-8.8	-5.3
26	3541.6	-15.6	-5.6
27	3541.6	-12.6	-5.6
28	3541.5	-8.5	-4.5
29	3541.5	-3.5	-2.5
30	3541.5	-1.5	-1.0
31	3541.5	-5.5	1.0
38	3541.2	-6.2	0.0
39	3541.3	-9.3	-3.3
40	3541.7	-6.9	-1.2
41	3542.2	-5.2	-0.2
42	3542.5	-6.0	-0.5
43	3542.4	-4.4	1.1
47	3536.1	-1.1	2.8
48	3535.9	-5.9	1.5
49	3535.7	-3.7	-1.7
58	3538.7	*	-7.7
59	3538.7	-7.7	-0.7
60	3538.7	-12.7	-2.4
61	3538.7	-12.7	-2.5
62	3538.7	-10.2	-1.8
63	3538.7	-6.7	-0.8

NOTE: Pressures are recorded in prototype feet of water to the nearest tenth of a foot.
Locations of piezometers are shown on plate 6.
* Denotes piezometer opening partially free of water.

TABLE 6

PRESSURES IN TUNNEL

Piez. No.	Station	Elevation	Pressure	Pressure	Pressure	Pressure	Pressure	Pressure
			One Outside Conduit in Operation			One Inside Conduit in Operation		
			Q, 1340 cfs	Q, 1080 cfs	Q, 710 cfs	Q, 1702 cfs	Q, 1300 cfs	Q, 910 cfs
73	7+83.2	3537.5	*	*	1.3	*	*	2.1
74	10+33.2	3537.0	*	2.9	1.2	*	3.7	2.0
75	12+83.2	3536.6	4.1	3.3	1.7	5.1	4.0	2.6
76	15+33.2	3536.2	4.4	3.7	2.1	5.5	4.2	3.0
77	17+83.2	3535.8	4.7	3.7	2.4	5.5	4.4	3.3
78	20+33.2	3535.3	5.2	4.2	2.9	5.7	4.8	3.6
79	22+83.2	3534.9	5.3	4.4	3.2	6.1	5.1	4.0
80	24+67.7	3534.6	6.1	5.4	4.2	6.9	5.9	4.9
Jump Location			Sta 10+40	Sta 8+00	Sta 5+00	Sta 11+75	Sta 9+00	Sta 5+40
			Two Conduits in Operation			Four Conduits in Operation		
			(2 Outside) Q, 2680 cfs	(2 Inside) Q, 3406 cfs	(1 Inside, 1 Outside) Q, 3035 cfs		Q, 3200 cfs	
70	0+33.2	3538.7	-	-	-		1.3	
71	2+83.2	3538.3	-	-	-		11.2	
72	5+33.2	3537.9	-	-	-		10.6	
73	7+83.2	3537.5	-	-	-		10.5	
74	10+33.2	3537.0	-	-	-		10.0	
75	12+83.2	3536.6	-	-	-		9.9	
76	15+33.2	3536.2	8.4	10.1	9.4		9.9	
77	17+83.2	3535.8	8.3	10.1	9.3		9.7	
78	20+33.2	3535.3	8.3	9.7	8.9		9.4	
79	22+83.2	3534.9	8.3	9.5	8.6		9.2	
80	24+67.7	3534.6	8.9	9.9	9.4		9.7	
Jump Location			Sta 13+80	Sta 14+50	Sta 14+00		Sta 1+90	

NOTES: Pressures are recorded in prototype feet of water.
* Denotes piezometer opening free of water.
Piezometers no. 64 to 69 above water surface and therefore omitted.

PLATES

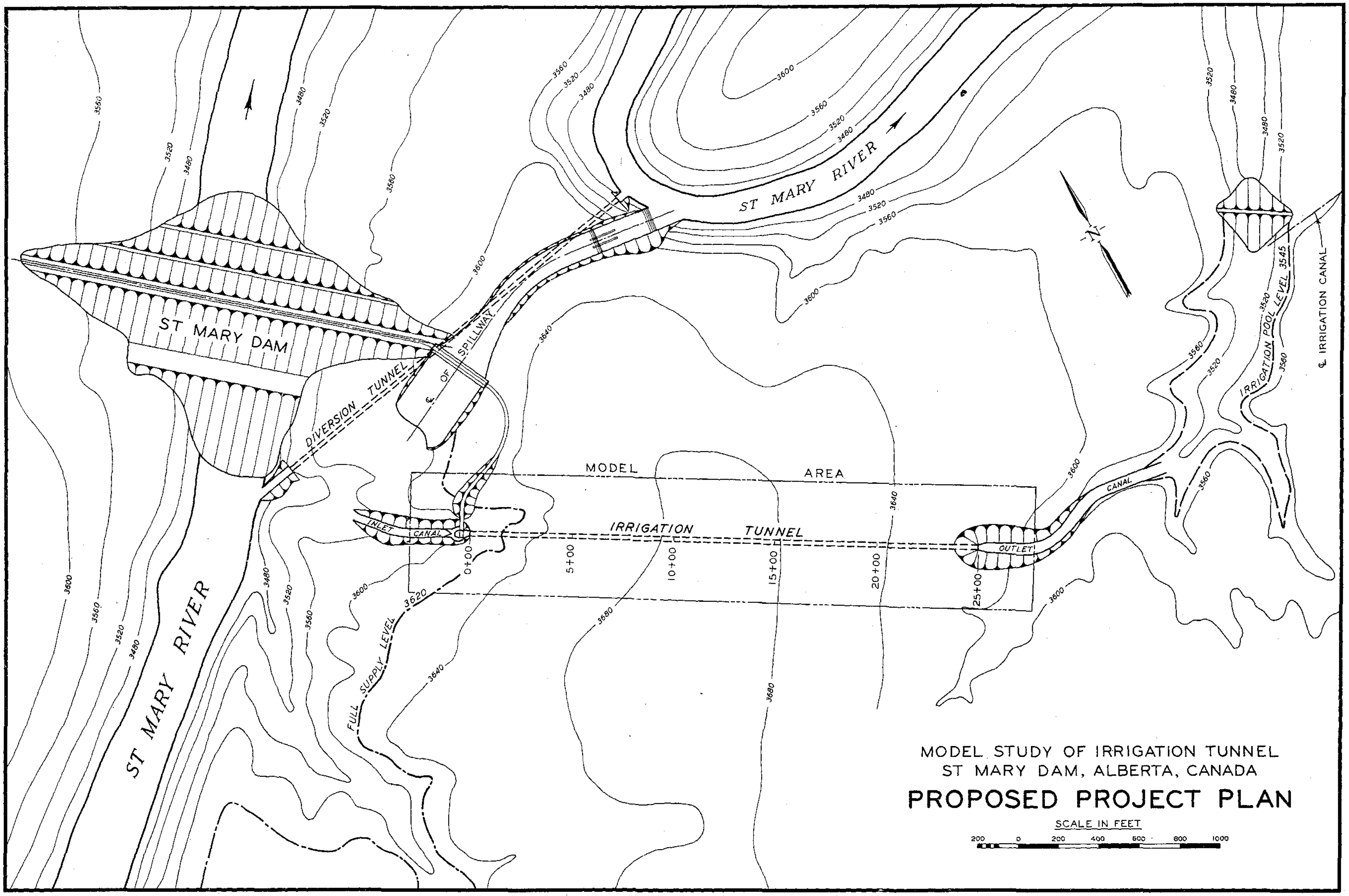
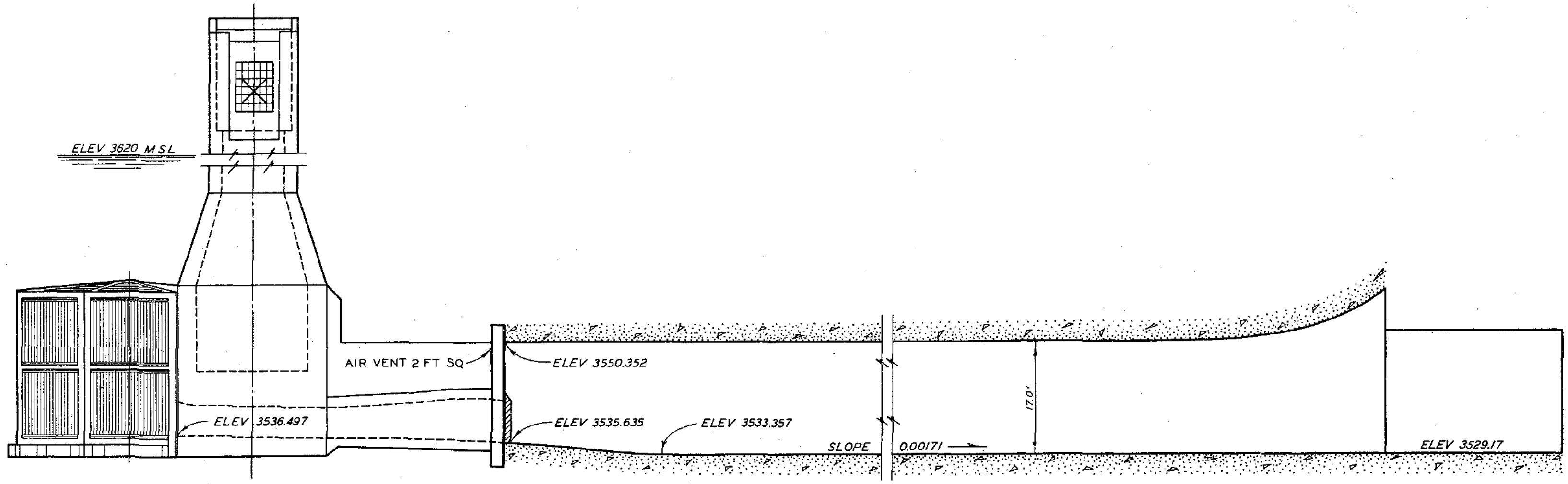

ST MARY DAM
DIVERSION TUNNEL
℄ OF SPILLWAY
ST MARY RIVER
ST MARY RIVER
MODEL AREA
IRRIGATION TUNNEL
INLET CANAL
OUTLET
CANAL
0+00
5+00
10+00
15+00
20+00
25+00
FULL SUPPLY LEVEL 3620
IRRIGATION POOL LEVEL 3545
℄ IRRIGATION CANAL
N
MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA
PROPOSED PROJECT PLAN
SCALE IN FEET
200 0 200 400 600 800 1000

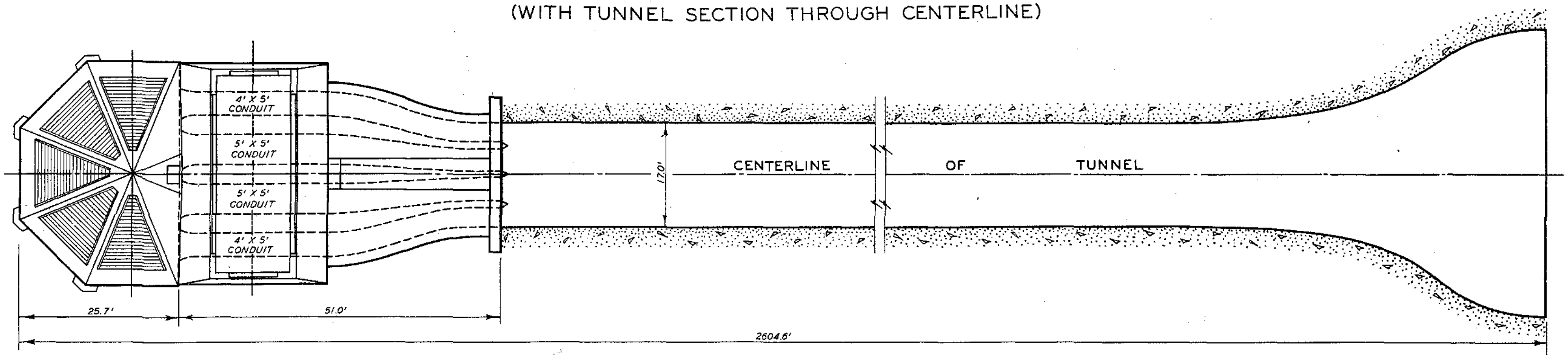
PLATE 1

PLATE 2



ELEVATION - CONTROL STRUCTURE

(WITH TUNNEL SECTION THROUGH CENTERLINE)



PLAN - CONTROL STRUCTURE

(WITH TUNNEL SECTION)

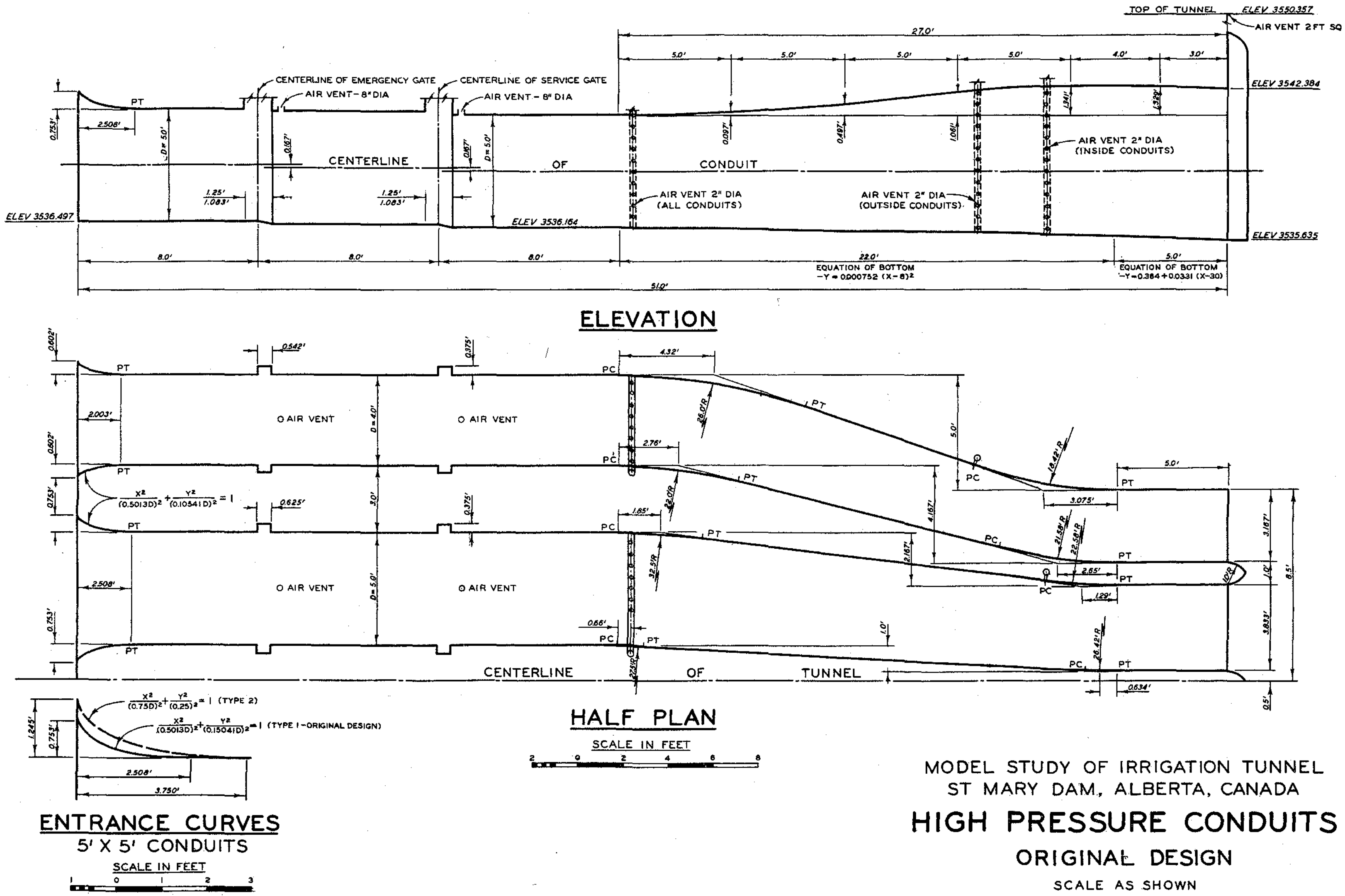
MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

PLAN AND ELEVATION

ORIGINAL DESIGN

SCALE IN FEET

10 0 10 20 30 40 50



MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

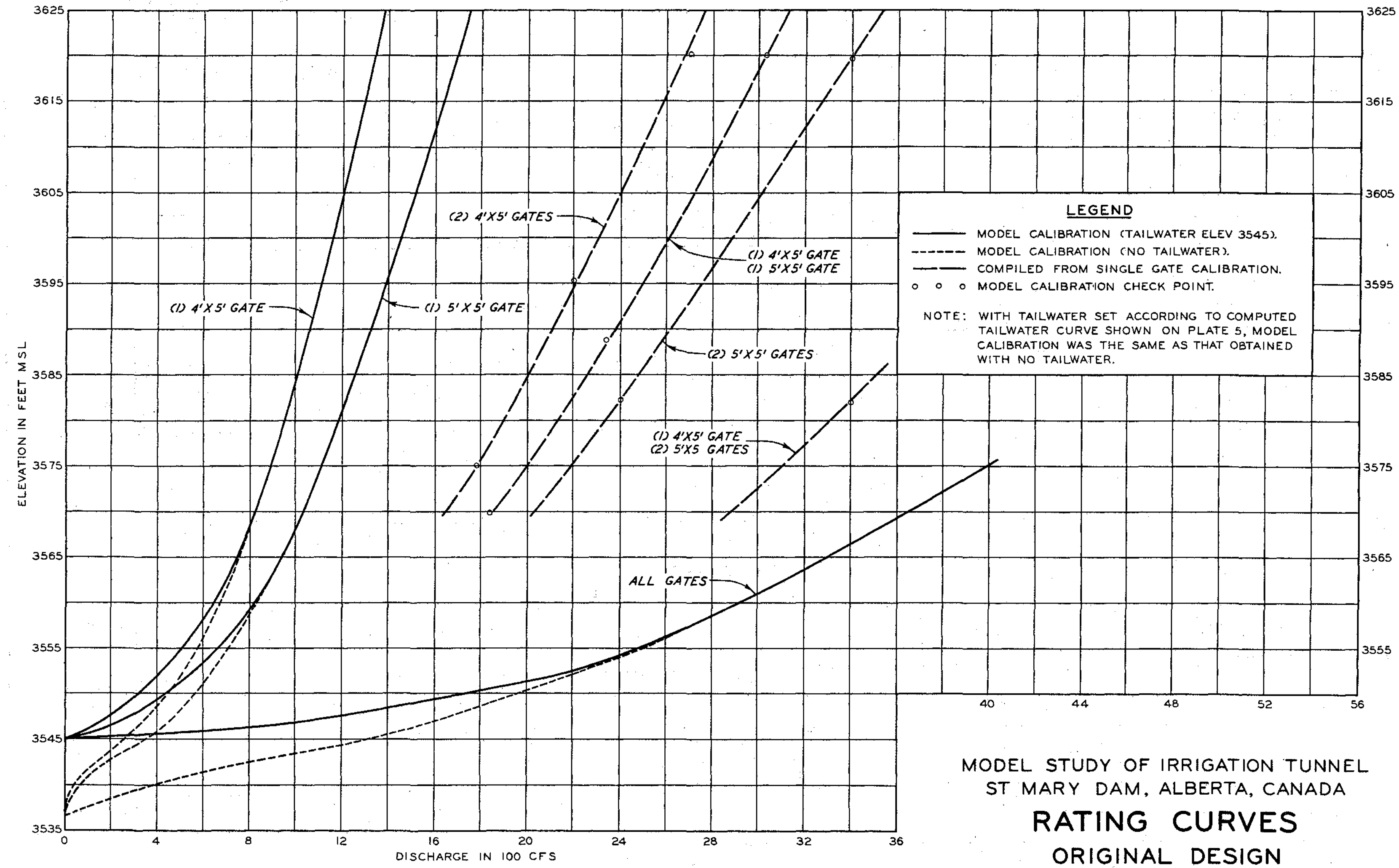
HIGH PRESSURE CONDUITS

ORIGINAL DESIGN

SCALE AS SHOWN

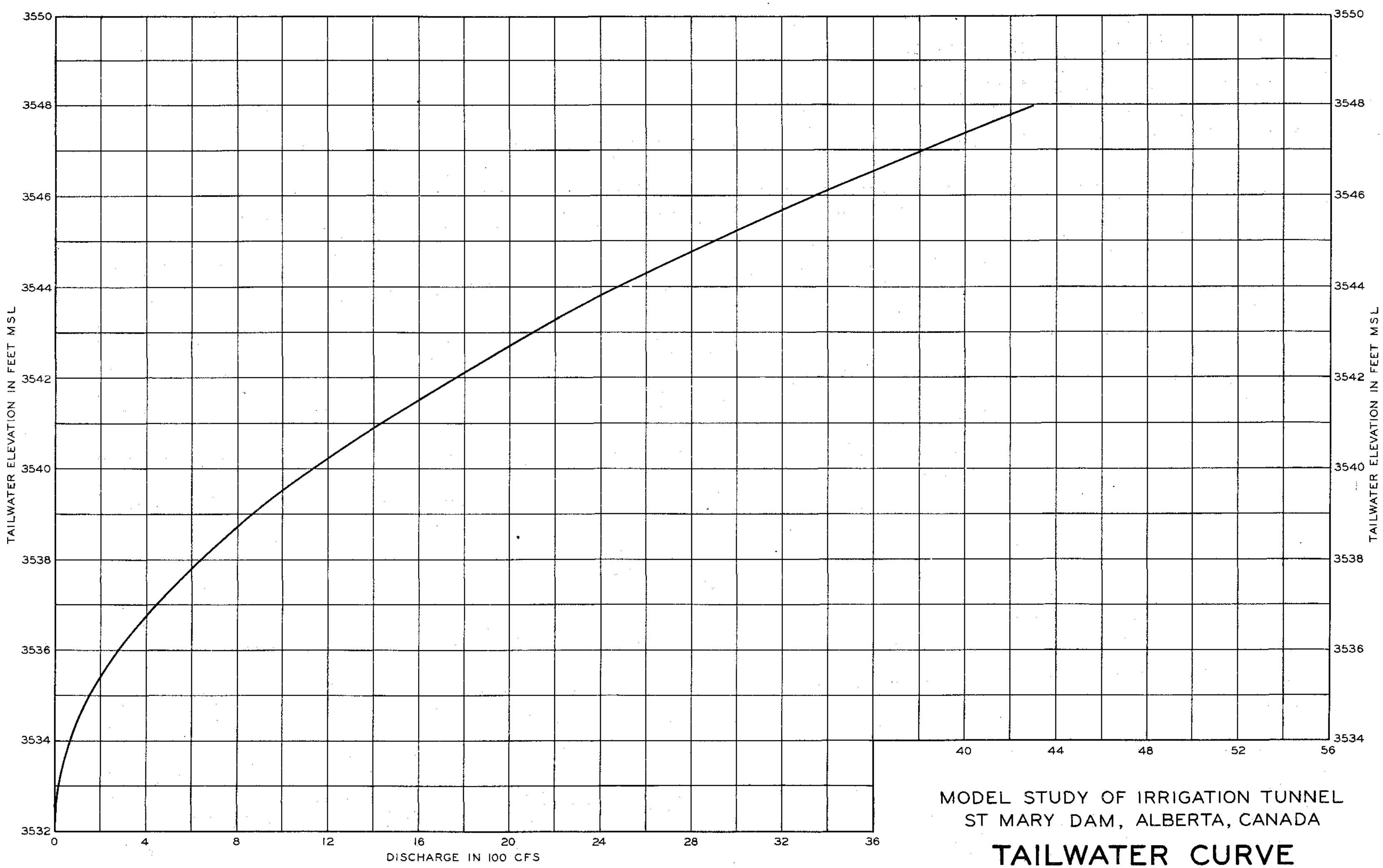
PLATE 3

PLATE 4



MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

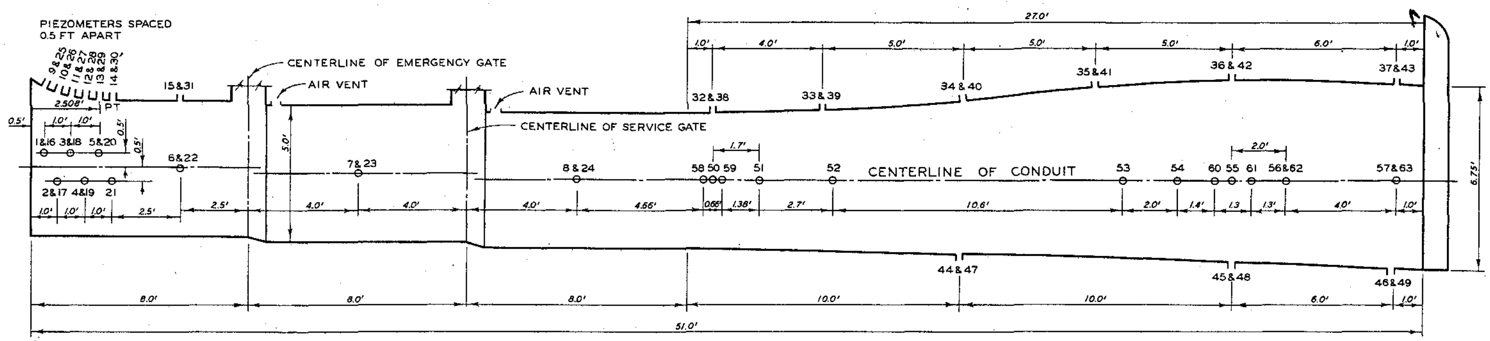
RATING CURVES
ORIGINAL DESIGN



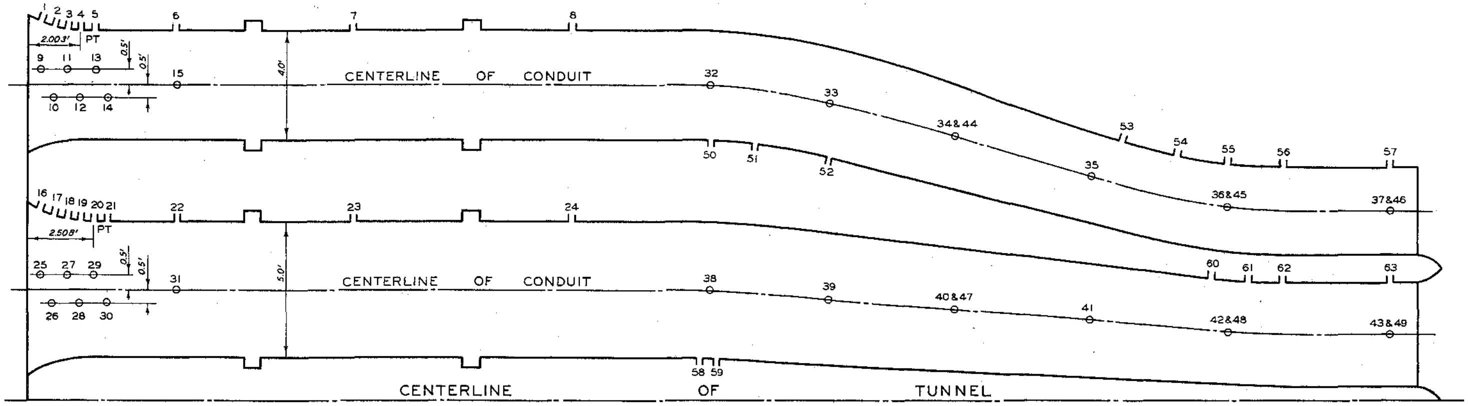
MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

TAILWATER CURVE

PLATE 5



ELEVATION

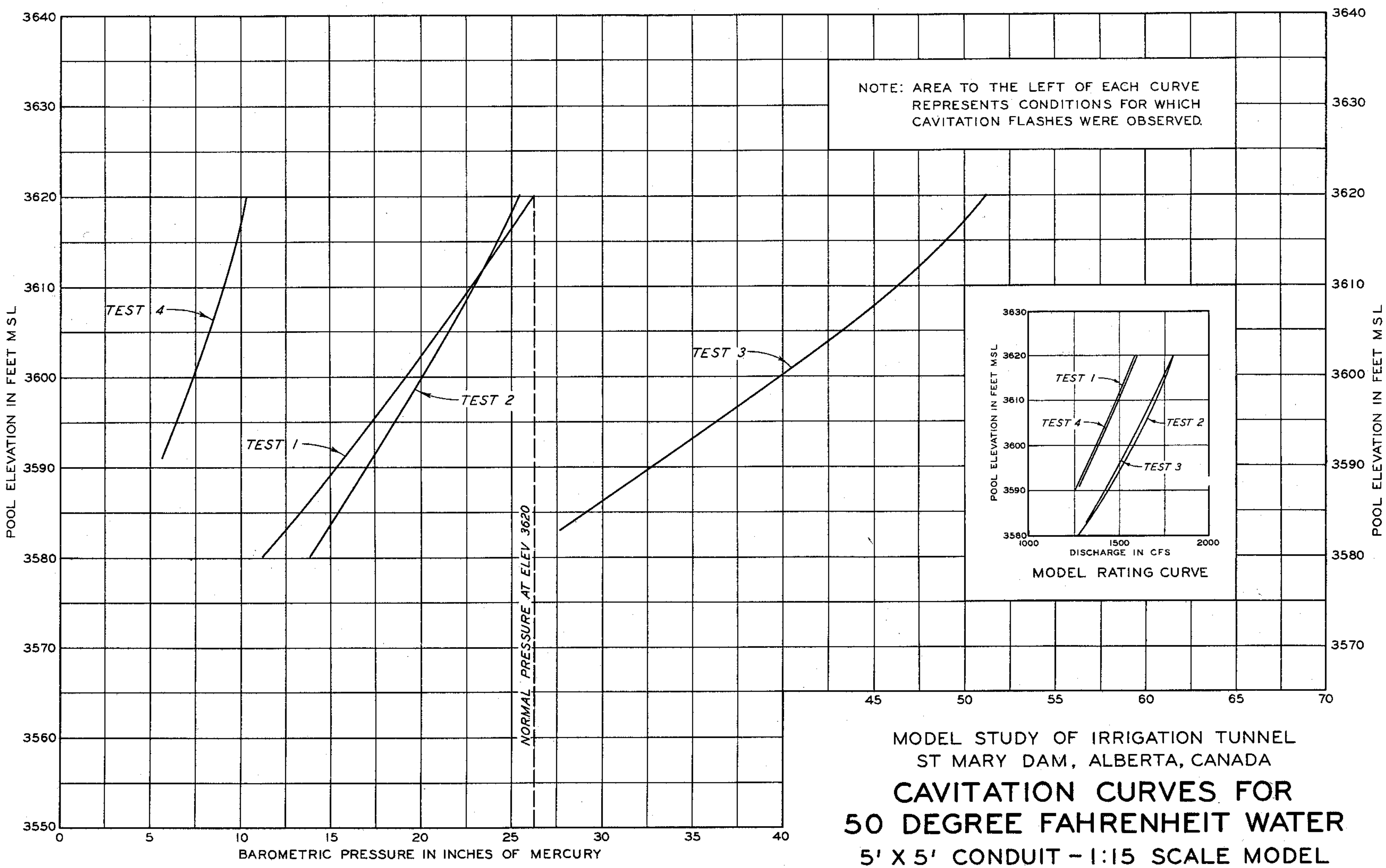


HALF PLAN

MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

PIEZOMETER LOCATIONS IN HIGH PRESSURE CONDUITS

SCALE IN FEET

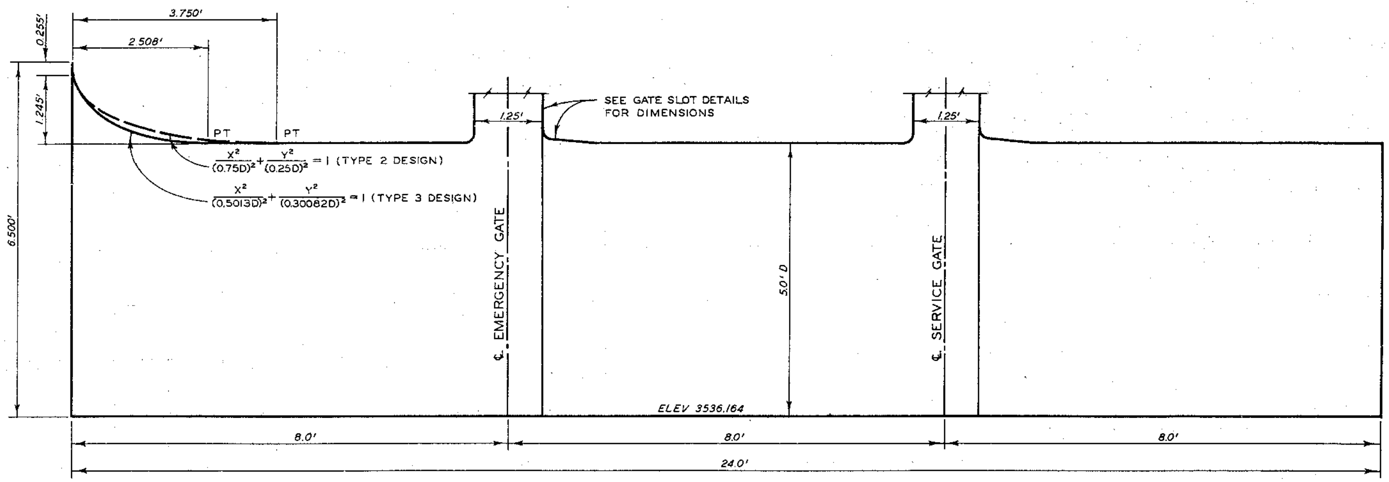


MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

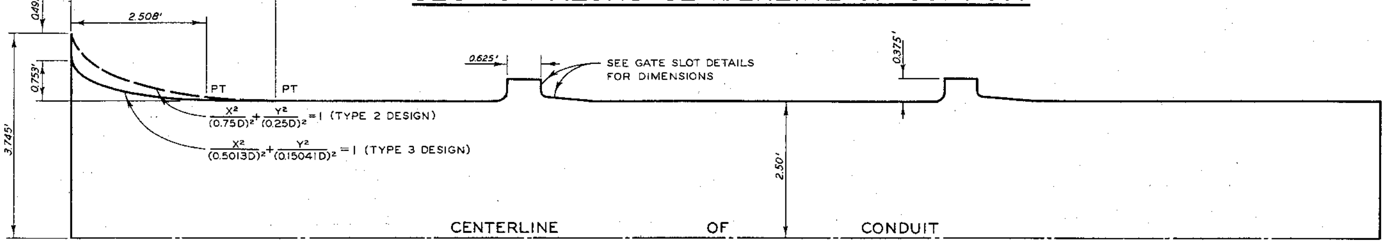
CAVITATION CURVES FOR 50 DEGREE FAHRENHEIT WATER

5' X 5' CONDUIT - 1:15 SCALE MODEL

PLATE 7



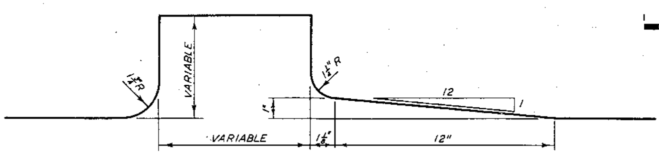
SECTION ALONG CENTERLINE OF CONDUIT



HALF PLAN

SCALE IN FEET

1 0 1 2 3 4 5



TYPE 2 GATE SLOT DETAILS

SCALE IN INCHES

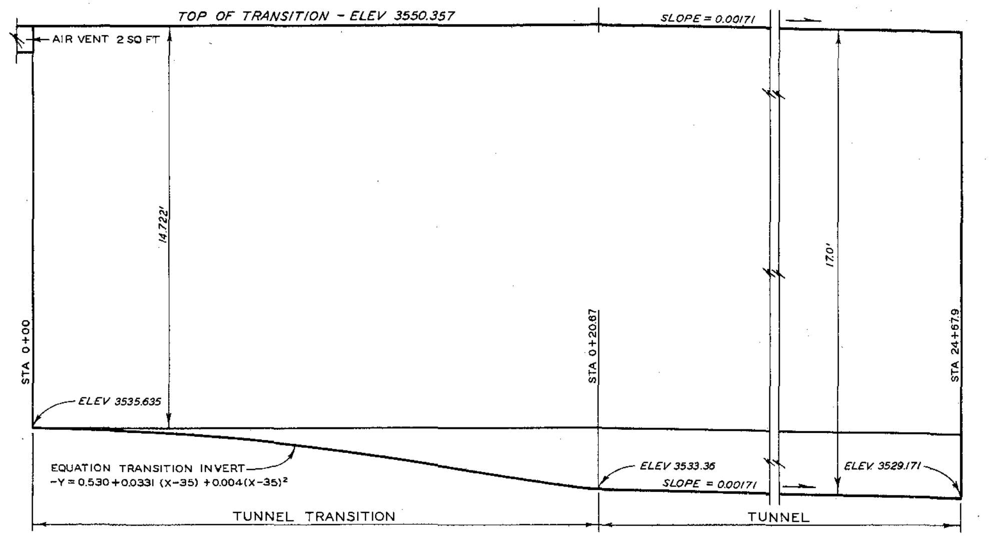
3 0 3 6 9 12

MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

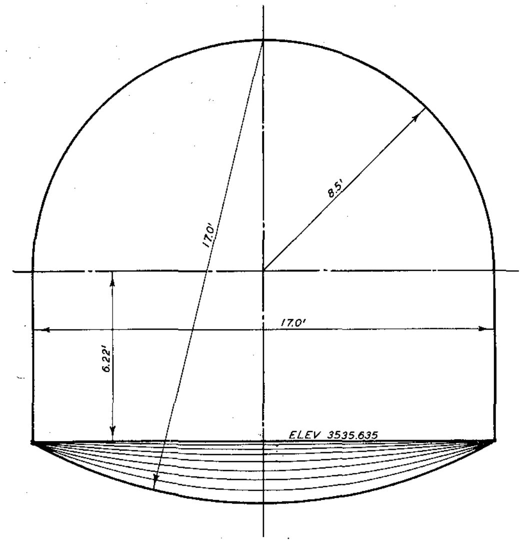
REVISED GATE SECTION
5' X 5' CONDUIT

1:15 SCALE SECTION MODEL

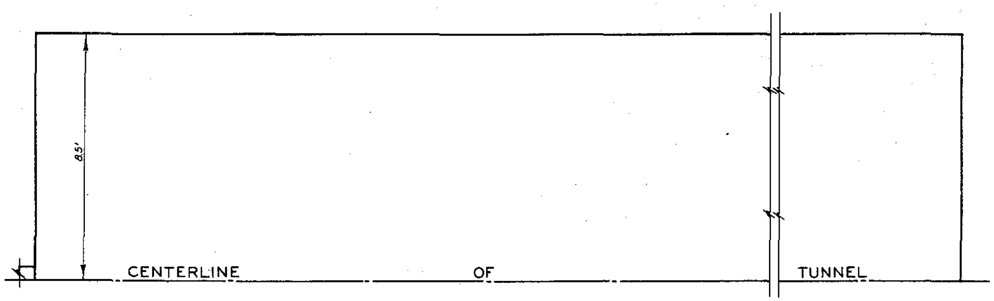
SCALE AS SHOWN



ELEVATION



ELEVATION AT STA 0+20.67



HALF PLAN

MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

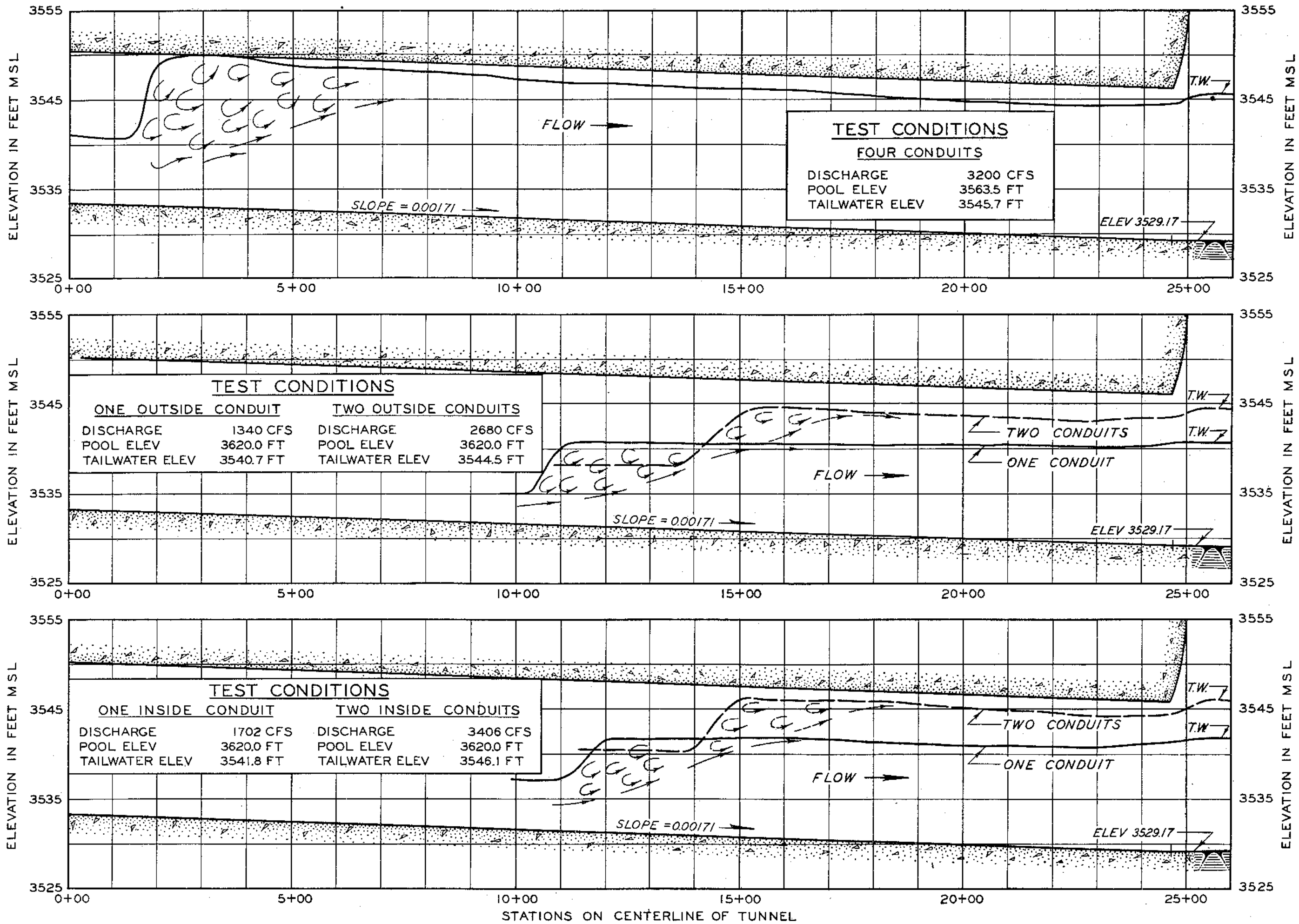
PLAN AND ELEVATION

TUNNEL TRANSITION AND TUNNEL

SCALE IN FEET

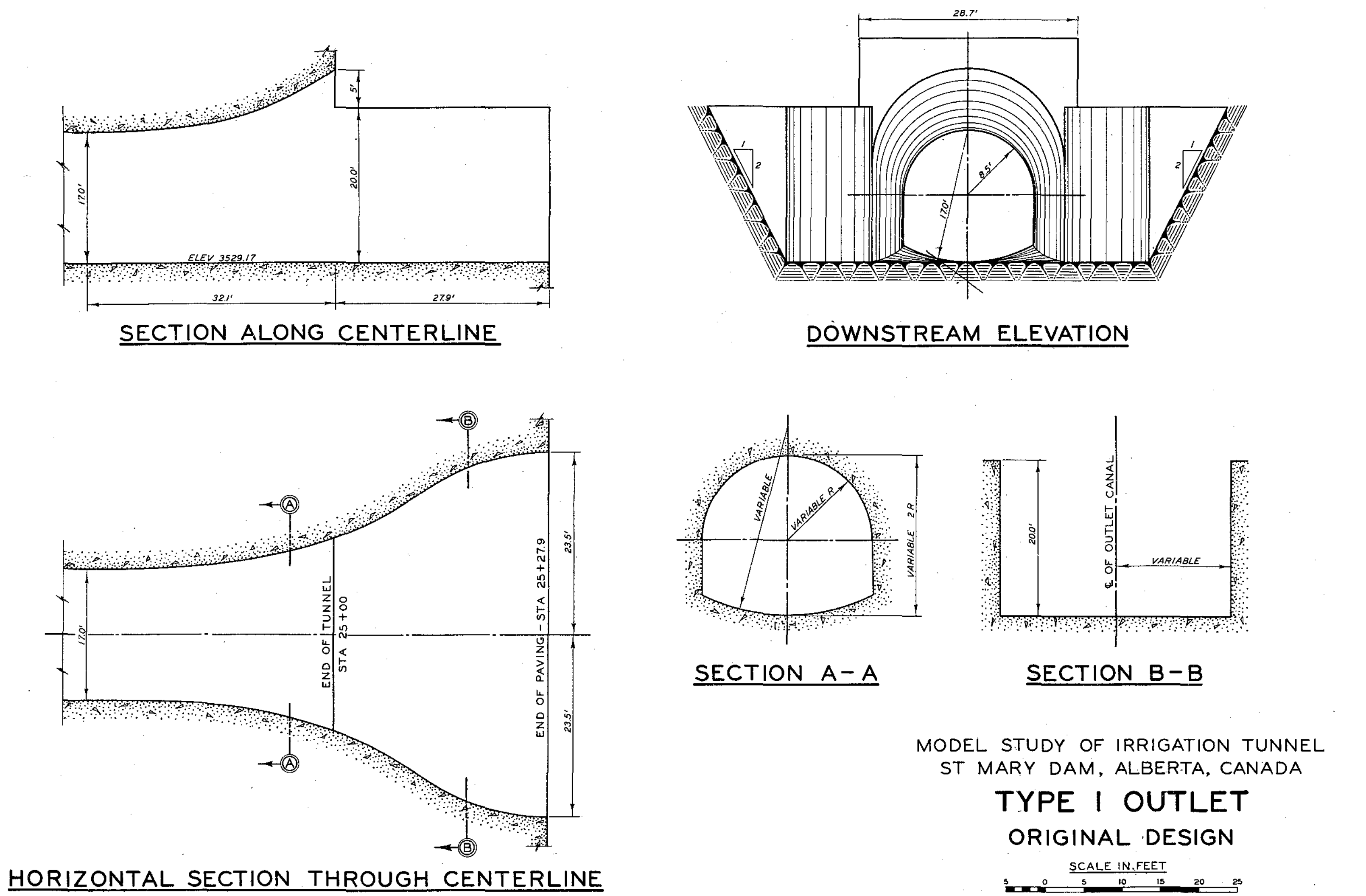
5 0 5 10

PLATE 9



MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

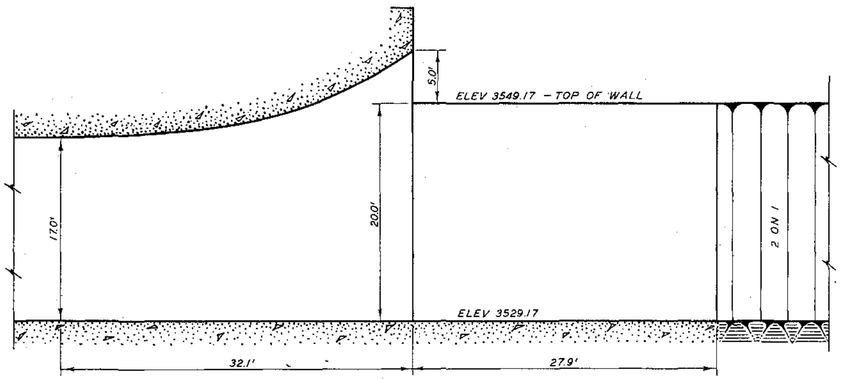
WATER-SURFACE PROFILES



MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

TYPE I OUTLET
ORIGINAL DESIGN

PLATE 12

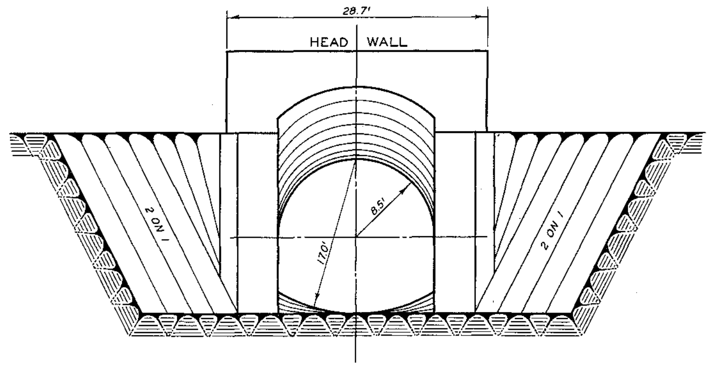


SECTION ALONG CENTERLINE

(WITH EXIT CANAL ELEVATION)

SCALE IN FEET

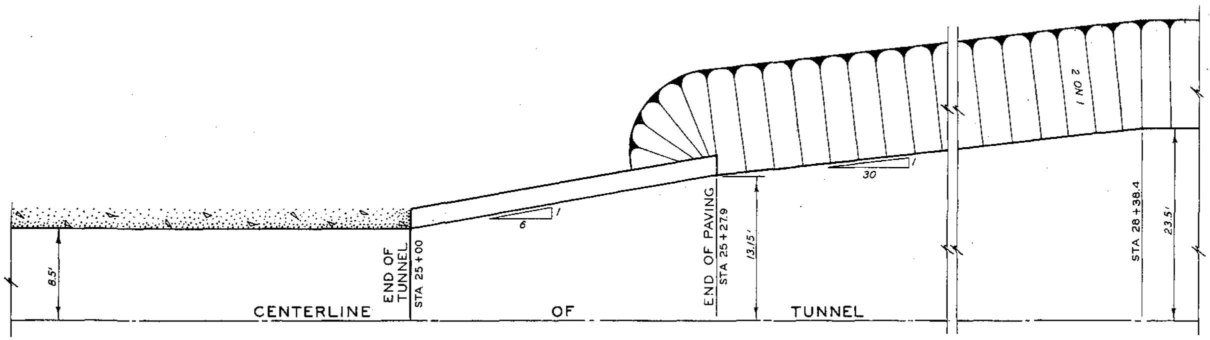
5 0 5 10 15 20 25



DOWNSTREAM ELEVATION

SCALE IN FEET

5 0 5 10 15 20 25



HALF PLAN – EXIT CANAL

(WITH TUNNEL SECTION)

SCALE IN FEET

5 0 5 10 15 20 25

NOTES: 1. TYPE 2 OUTLET SAME AS TYPE 4 EXCEPT 47-FT TRAPEZOIDAL CANAL EXTENDED TO END OF PAVING.

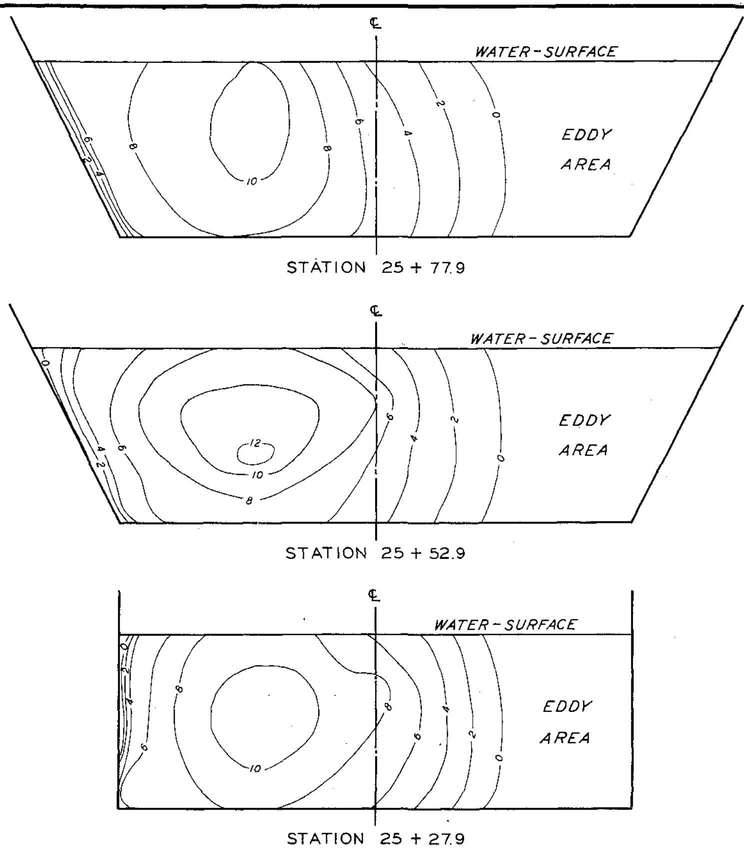
2. TYPE 3 OUTLET SAME AS TYPE 4 EXCEPT EXCAVATED ON 1 ON 6 FLARE FROM STATION 25+27.9 TO A WIDTH OF 47-FT AT STATION 25+90.

MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

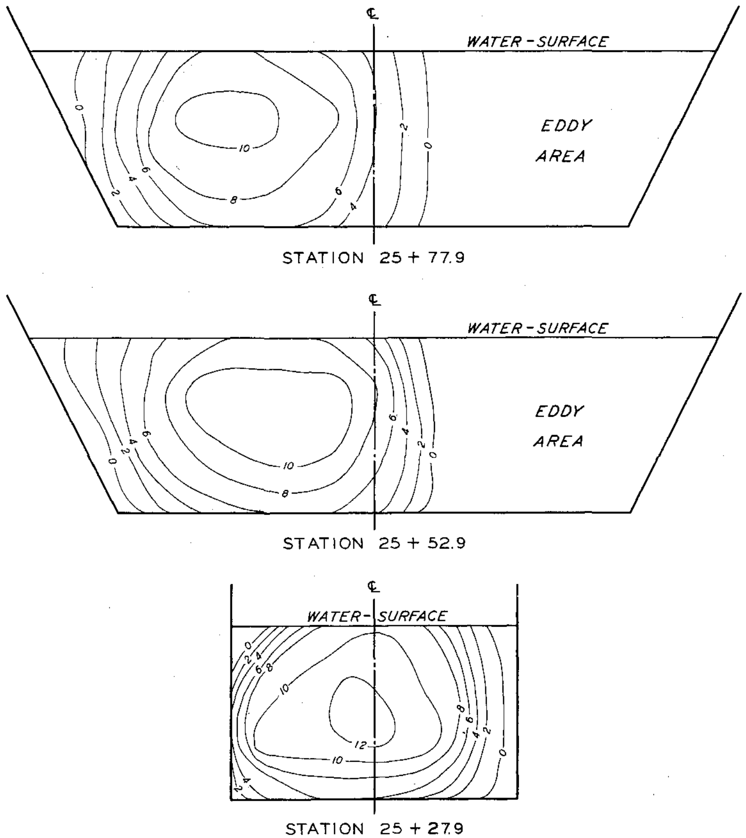
TYPE 4 OUTLET

FINAL DESIGN

SCALE AS SHOWN



TYPE 1 OUTLET



TYPE 2 OUTLET

TEST CONDITIONS

FOUR CONDUITS

DISCHARGE	3200 CFS
TAILWATER ELEV	3545.0 FT
CANAL ELEV	3529.17 FT

NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND.

MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

VELOCITY DISTRIBUTION-EXIT CANAL

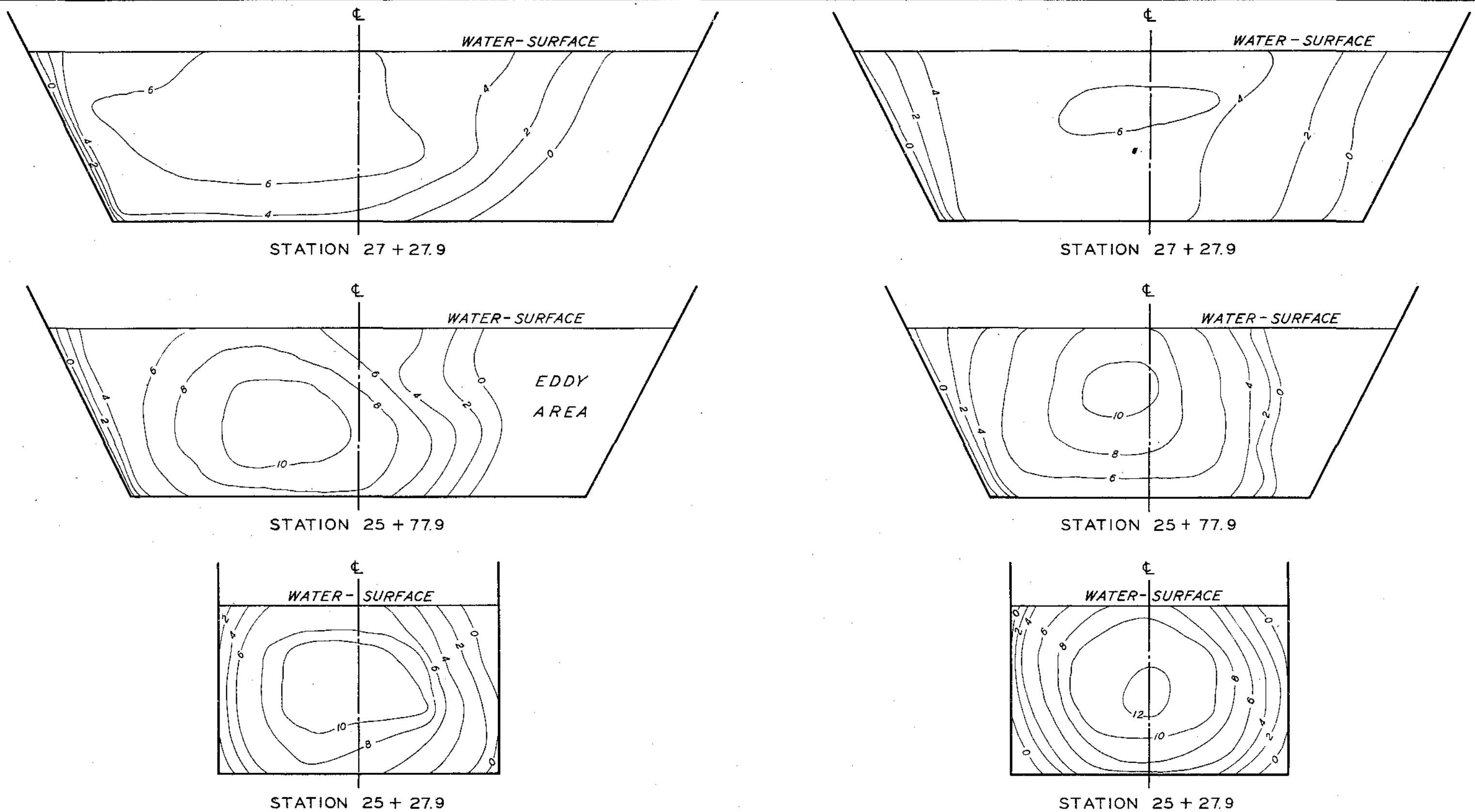
TYPES 1 AND 2 OUTLETS

SCALE IN FEET

10 0 10 20 30

PLATE 13

PLATE 14



TYPE 3 OUTLET

TYPE 4 OUTLET

TEST CONDITIONS

FOUR CONDUITS

DISCHARGE	3200 CFS
TAILWATER ELEV	3545.0 FT
CANAL ELEV	3529.17 FT

NOTE: VELOCITIES ARE IN PROTOTYPE FEET PER SECOND.

MODEL STUDY OF IRRIGATION TUNNEL
ST MARY DAM, ALBERTA, CANADA

VELOCITY DISTRIBUTION-EXIT CANAL

TYPES 3 AND 4 OUTLETS

SCALE IN FEET

10 0 10 20 30